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Mirror characterizing for Cherenkov telescopes

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Mirror characterizing for Cherenkov telescopes

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“The truth is a beautiful and terrible thing, and should therefore be treated with caution.”

J.K. Rowling (Albus Dumbledore, Harry Potter and the Sorcerer’s Stone, 1997)

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ABSTRACT

DIPOLD, J. **Mirror characterizing for Cherenkov telescopes**. 2015. 121 p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2015.

γ -rays are billions of times more energetic than visible photons. Through the sky observation of this kind of radiation, it is possible to study phenomena like the emission from pulsars, supernova explosions and black holes, as well as gamma-ray bursts, one of the greatest mysteries in modern astrophysics. The main technique used in astrophysical observations in γ -rays showers is the Imaging Cherenkov Telescope, which can image the trajectory of gamma-rays during its passage through the atmosphere by observing its emission of Cherenkov radiation. There are several successful experiments currently functioning, such as VERITAS, MAGIC and HESS. In 2006, a new observatory was proposed, which will have a sensitivity one order of magnitude better than any of the existing experiments. The Cherenkov Telescope Array (CTA) is in its prototype phase, and will consist of several tens of Cherenkov telescopes with different sizes, which will allow observation in many different regions of the γ -ray spectrum. The site where the Observatory will be constructed is not yet decided and it depends on several geographic characteristics, being one of the most important the observable time, which must be above 80% to be considered as a possible site. One of the proposed sites is located in the north of Argentina, close to the city of San Antonio de los Cobres (SAC). In order to demonstrate the functionality of the site, we developed a facility on it to test the optical and mechanical properties of four prototype mirrors, as well as their condensation conditions. Three Glass/Aluminum hexagonal mirrors, 1.5 meters flat-to-flat diameter, and one Glass/Dielectric circular mirror, 0.5 meters diameter, all spherical with a focal position between 15 and 16 meters, were exposed to the environmental conditions of SAC from May/2013 until June/2014. To test their mechanical and optical properties variation because of the environment exposition, two different tests were made. In order to verify if the curvature and smoothness of the mirrors remained constant, we developed an equipment at the Instituto de Física de São Carlos that could measure the $2f$ position, where the image formed by the mirror is the smallest as possible, and its Point Spread Function (PSF), the size of the image made by the mirror by a punctual source. The focal position of all mirrors was proven to be stable, while the PSF size showed small differences according to the exposure time. To examine the variation of the Aluminum (or Dielectric) covering of the mirrors we measured its reflectivity variation through a portable spectrometer fabricated by OceanOptics, which showed that the dielectric covering is more stable than the Aluminum ones, even though all of them showed a constant reflectivity in the 300-400 nm range. And finally, to test both the mirror and the site quality in observation time, we calculated the condensed time of two mirrors during the period of December/2013 until April/2014. This was done through automatic pictures of each mirror taken remotely during the night, providing data to observe daily changes in the quality of the mirror surfaces as well as if there is condensation during that period. A Glass/Aluminum mirror and the Glass/Dielectric one were tested, both showing very similar results of around 20% condensed time, being in the limit of the 80% of observational time forementioned. Through these tests, we intend to provide a technique for the calculation of condensed time in any proposed site.

Keywords: Mirrors. Gamma-rays. Cherenkov Telescope Array.

RESUMO

DIPOLD, J. **Caracterização de espelhos para telescópios Cherenkov**. 2015. 121 p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2015.

Raios γ são bilhões de vezes mais energéticos do que fótons visíveis. Através da observação do céu deste tipo de radiação, é possível estudar fenômenos como a emissão de pulsares, explosões de super-novas e buracos negros, assim como os *gamma ray bursts*, um dos maiores mistérios da astrofísica moderna. A principal técnica utilizada em observações astrofísicas de chuveis de raios gama é a de Telescópios Cherenkov, que podem reconstruir a trajetória dos raios γ durante sua passagem pela atmosfera observando sua emissão de radiação Cherenkov. Existem diversos experimentos bem-sucedidos em funcionamento, tais como o VERITAS, MAGIC e HESS. Em 2006 um novo observatório foi proposto, com sensibilidade uma ordem de magnitude melhor do que qualquer outro experimento atual. O *Cherenkov Telescope Array* (CTA) está em fase de protótipo e consistirá de dezenas de telescópios Cherenkov com tamanhos diferentes, o que possibilitará observações em muitas regiões do espectro de raios-gama. O local onde o Observatório será construído ainda não foi decidido e dependerá de várias características geográficas para fazê-lo, sendo uma das mais importantes o tempo observável, que deve ser maior que 80% para ser considerado um possível sítio. Um dos locais propostos está localizado no norte da Argentina, próximo a cidade de San Antonio de los Cobres (SAC). Para demonstrar a funcionalidade deste sítio, desenvolvemos um espaço nele para testarmos propriedades ópticas e mecânicas de quatro protótipos de espelhos, além de suas condições de condensação. Três espelhos hexagonais de Vidro/Alumínio, com 1.5 metro de base a base, e um circular de Vidro/Dielétrico, com 0.5 metro de diâmetro, todos esféricos com posição focal entre 15 e 16 metros, foram expostos às condições ambientais de SAC entre Maio/2013 até Junho/2014. Para testar a variação de suas propriedades mecânicas e ópticas devido à exposição ao meio ambiente, dois testes foram feitos. Para verificar se a curvatura e a suavidade da superfície do espelho permaneceram constantes, desenvolvemos um equipamento no Instituto de Física de São Carlos que mede a posição $2f$ do espelho, onde a imagem formada é a menor possível, e sua Função Ponto Espalhada (PSF), o tamanho da imagem feita pelo espelho de uma fonte pontual. A posição focal de todos os espelhos foi estável, enquanto a PSF mostrou pequena variação com o tempo de exposição. Para analisar a variação da cobertura de Alumínio (ou Dielétrico) dos espelhos, nós medimos a variação de sua refletividade através de um espectrômetro portátil fabricado pela OceanOptics, que mostrou que a cobertura dielétrica é mais estável do que as de alumínio, que tiveram pouca variação entre 300-400 nm na maioria dos espelhos. E, finalmente, para testar a qualidade de ambos espelho e sítio em relação ao tempo de observação, calculamos o tempo de condensação de dois espelhos durante o período de Dezembro/2013 até Abril/2014. Isso foi feito através de fotos automáticas de cada espelho tiradas remotamente durante a noite, fornecendo dados para observar mudanças diárias na qualidade da superfície dos espelhos assim como a condensação durante esse período. Um espelho de Vidro/Alumínio e um de Vidro/Dielétrico foram testados, ambos mostrando resultados similares de aproximadamente 20% de tempo condensado, estando no limite de 80% de tempo observacional mencionado anteriormente. Através destes testes, pretendemos criar uma técnica para o cálculo do tempo de condensação em qualquer sítio proposto.

Palavras-chave: Espelhos. Raios Gama. Cherenkov Telescope Array.

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CHAPTER 1

Introduction

Modern astronomy was probably founded in 1609, when Galileo did his first astronomical observations through optical telescopes. Afterwards, astronomers explored the Universe through the observation of phenomena in the visible spectrum, investigating the so-called thermal Universe. (1) In 1912, the physicist Victor Hess, by flying on a balloon to do an experiment (2), showed that the air ionization increased with the altitude and concluded that some type of high-energy radiation is constantly bombarding Earth from space. These particles were later called “*cosmic rays*” by Millikan, in 1925. The study of cosmic rays led to important discoveries concerning its generation, propagation and interactions in the atmosphere.

There are several kinds of particles that arrive on Earth, such as protons, different nuclei and gamma rays. The latter one developed a new branch of study in the Cosmic Ray Astrophysics, intensified in the 1980s when TeV gamma-ray emissions from the Crab Nebula were detected. At first, the observation of gamma rays was mainly done by detectors flown in spacecrafts, which was the obvious choice since the photon beams were attenuated by the atmosphere. This technique was strongly developed and is operational in experiments such as Fermi LAT. (3) A complementary technique was developed based on the detection of the air shower produced by the gamma-ray interaction in the atmosphere. Imaging Atmospheric Cherenkov Telescopes (IACTs) (4) were built to measure the Cherenkov light produced by the charged particles in the shower. These telescopes reflect the Cherenkov radiation emitted by particles in the atmosphere in arrays of photomultipliers. The detected image of the shower can be reconstructed in order to find the direction and energy of the primary gamma ray. The detection of a large number of showers coming from the same direction allows the construction of a source map and an energy spectrum. A description about the gamma-ray induced showers will be shown in Chapter 2.

The first successful IACT experiment was the Whipple telescope in Arizona, USA, composed of a reflector of 10 meters diameter. It was the first to detect the TeV gamma-ray emissions from the Crab Nebula (5), and was responsible for increasing the interest in Very High-Energy Gamma-Ray Astronomy. Given its success, a new generation of

telescopes was designed to study fainter sources. This second generation of IACTs aimed to obtain a stereoscopic view of the shower by constructing more than one telescope in the same site, increasing the sensitivity and the angular resolution of the observations. Several arrays of IACTs were built, such as H.E.S.S. (6), VERITAS (7) and MAGIC (8). The detection technique is going to be further discussed in Chapter 3, where a short description of the second generation experiments will be presented. These experiments have detected more than a hundred sources of gamma rays with energies above 100 GeV. (9) Interesting results are still being published, for examples see References (10–13).

Based on the success of the second generation of IACTs experiments, a new Observatory was proposed in 2006: The Cherenkov Telescope Array (CTA). (14) CTA will increase the sensitivity in one order of magnitude in relation to the current telescopes. The project has over 1000 researches of 27 different countries, and is currently in the prototyping phase. CTA will consist of over 100 Imaging Atmospheric Cherenkov Telescopes spread out in a ~ 1 km area in two different sites, one in the northern hemisphere and one in the southern one. These telescopes will have three different sizes in order to cover a large energy range, between 30 GeV up to 100 TeV. CTA is designed to allow the study of the origin of cosmic rays through the investigation of acceleration processes, black hole particle accelerators and the examination of nature beyond the Standard Model, searching for dark matter and effects of quantum gravity. (14)

Since the Observatory is in its prototyping phase, there are several tests underway in the individual components of the telescopes and in the proposed sites. The mirror facets is one of the main parts of the telescopes and nearly 10000 m^2 will be fabricated only for the southern site. Therefore, it is necessary to test different manufacture techniques to find which one has the best cost/effectiveness ratio as possible while keeping within the requirements proposed by the CTA Consortium. (15) The site where the Observatory will be constructed has also been thoroughly tested (16) for over a year, storing data of weather conditions, such as cloudiness, temperature variation, wind and humidity. All these characteristics affect the operational time of the telescopes, which is targeted to be above 80% during the year.

This work aims to assist in the choice of both the mirror facets and the site where the Observatory will be constructed. In order to do that, in a collaboration with the groups from the National Commission of Atomic Energy (CNEA) and the Argentinian Institute of Radio Astronomy (IAR), we developed a facility in San Antonio de los Cobres (SAC), one of the proposed sites for CTA. The facility was constructed with the aim of studying the behaviour of prototype mirrors in the operational conditions of the site. We exposed four

prototype mirrors from May/2013 until June/2014. During this period, we measured the Point Spread Function variation of the mirrors, as well as their reflectivity, to analyse if the shape of the mirrors changed and if their aluminum coating was damaged. We also studied the influence of the site weather conditions on the mirrors through the observation of condensation in its surfaces. We calculated the time that two of these mirrors were condensed during the night, giving an estimation of the operational time the telescopes would have in the SAC site. The procedures used during the optical and mechanical tests are described during Chapter 4.

We discovered that all the mirrors are mechanically stable, and therefore the technology is adequate to be used on site. However, the reflectivities of the aluminum mirrors suffered big losses, of more than 4% during six months of exposure, which indicates that the covering quality or its protective coating is not sufficiently resistant to weather conditions. The mirrors condensed for approximately 19% of the time, indicating a loss of observational time of $\sim 20\%$ at the San Antonio de los Cobres only by this characteristic. This leaves the SAC site in the border of the CTA site requirements, which proposes 80% of observational time. These results are further explored during Chapter 5.

CHAPTER 2

High Energy Cosmic Rays

The studies of High Energy Cosmic Rays increased with Victor Hess, in Austria, when he used a balloon to measure the ionization rate of the air (2), which he believed that was related to gamma-ray radiation in high altitudes. (17) He discovered that the ionization increased with the altitude, and concluded that the only solution for this was that the radiation came from outside the atmosphere, with a strong penetration power. The particles that caused the ionization of the air were later called “*cosmic rays*” by Millikan, once he confirmed Hess’ experiments.

Many new particles were observed through the cosmic rays observations in the following years. (18) One of the main discoveries were the cosmic rays induced showers (Section 2.1), ascertained in 1938 by Pierre Auger. (19) He discovered the extensive air showers when two particle detectors separated by several meters signaled the arrival of a particle at the same time. Different techniques were developed to observe cosmic rays and identify their particles, such as cloud chambers, emulsion photographs, underground detectors for protons, scintillators, among others. Particles such as protons, different nuclei and gamma rays were observed as shower generators, and the latter one (Section 2.2) generated a whole branch of new studies.

2.1 Atmospheric Showers

Cosmic-ray showers are cascades formed by cosmic rays that interact with atmospheric nuclei. (17) The study of atmospheric showers is, today, the only mean of obtaining an indirect measurement of the properties of ultra high energy particles ($> 10^{18}$ eV). These particles have a flux so low that is not possible to directly observe them, but they generate a large quantity of secondary particles in its showers that cover a large area ($\sim 1 \text{ km}^2$) that are easier to detect.

The most simple form to describe the formation of the atmospheric showers can be seen in Figure 2.1. On it, there is one particle that interacts with the atmosphere at

a certain distance $\mathbf{X}$, generating, then, two identical particles with half of the original energy. The $\mathbf{X}$ distance is the particle mean free path. After traveling the same distance $\mathbf{X}$ again, these two particles interact and form two particles each, with $1/4$ of the original particle energy, and so on. This mechanism continues until the shower reaches a critical energy, below which there are no more interactions. The position where this occurs is called X_{max} , where the maximum number of particles that the shower can produce are located. This model was suggested by Heitler (20) and explains the basic mechanism of electromagnetic showers.

There are two types of atmospheric showers: hadronic and electromagnetic. The first ones are produced by protons and different nuclei. At their first collision with the nuclei in the atmosphere, mainly pions and kaons are created, either charged or not charged. These collide with more nuclei, creating secondary cascades (electromagnetic or muonic) or decaying in other particles (such as electrons, positrons, photons and neutrinos). (21) Electromagnetic showers are started by gamma-rays (photons), electrons or positrons. Showers initiated by photons generates electron-positron pairs, that by bremsstrahlung generates more photons, and so on. (22) The charged particles produced in these interactions emits Cherenkov radiation, which will be describe in the next section. Both types of showers increase their number of particles until an energy limit, when the ionization processes are stronger than the interaction and the shower starts to decrease in size.

Figure 2.1 – Heitler’s toy model, with a critical energy $E_c = E_0/128$. $\mathbf{X}$ is the particle mean free path, $\mathbf{N}$ is the number of particles in that point and $\mathbf{E}$ is the energy fraction of the initial energy E .

Source: STANEV, T. (17).

2.1.1 Cherenkov Radiation

Gamma-rays impinging the atmosphere collide with nuclei and produce charged particles. These charged particles can be considered to be inside a dielectric medium, of a refraction index $n > 1$. If the particles have a velocity larger than the phase velocity of light ($\frac{c}{n}$), they are moving faster than the electromagnetic information, inducing a polarization in the dielectric. A conical shaped wave front is formed at an angle θ_c (Figure 2.2), and this emitted radiation is called Cherenkov Radiation. (23)

Figure 2.2 – Illustration of Cherenkov Radiation emission, where $\theta_C = \frac{c}{v \times n}$ and $\mathbf{v}$ is the velocity of the particle in the medium. It is shown that the emission is only conical when the particle is with a velocity ($\mathbf{v}$) larger than the light velocity.

Source: JACKSON, J. D. (23).

Since the Cherenkov emission is coherent, it offers a large signal in comparison to the standard night background. The intensity of the Cherenkov light emission provides an energy measurement, which is proportional to the quantity of particles produced in the cascade.

The emission of Cherenkov radiation in the shower can be didactically divided in three portions shown in Figure 2.3 for a typical 1 TeV gamma ray. (24) The first portion, located between the first interaction point and 10 km of altitude, generates $\sim 25\%$ of the light. The Cherenkov angle increases as the particle descend in the atmosphere, forming a focused 'ring' with radius around 120 m. Since in the upper part of the atmosphere the light travels faster ($\frac{c}{n}$) than in the lower part, the spread of the light pulse at the typical observation level is very small (~ 1 ns). The second portion is where most of the light ($\sim 50\%$) is generated. It is concentrated inside a cylinder of different sizes depending on the energy of the primary particle (responsible for generating the shower) of the shower core. The shower maximum is in this region, therefore measuring the light produced

in this part of the shower is very important to improve the energy reconstruction. The last 25% of light is generated below 6 km of altitude, in the third portion of the shower, centrally focused and with large fluctuations, since it is dominated by the few remaining particles.

Figure 2.3 – Cherenkov emission regions of gamma-ray and proton showers. The picture shows the height of the shower versus its cone diameter. The area inside the broken line is for the proton shower of 1 TeV, while the shaped area is for the 1 TeV gamma-ray showers.

Source: WEEKES, T. (24).

The emission spectrum of the Cherenkov light is continuum, as seen in the curve (a) of Figure 2.4, and it varies with $\sim \frac{1}{\lambda^2}$. The relevant region of the emitted spectrum is between 250 nm and 600 nm. Its intensity varies largely with the altitude because of the atmospheric absorption. In the curve (d) in Figure 2.4 the transmission of the Cherenkov light is shown in the region where its observation is more common, between 10 and 2.3 km of altitude. Another important factor that decreases the observation capability is the background light which comes from the moon, nearby cities or stars, for example. This effect is weaker for small wavelengths, as seen in the curve (b) in Figure 2.4. All these factors make the optimum observation wavelength between 300-400 nm.

The use of reflectors that operate with a high reflectivity in the 300-400 nm is necessary in order to observe the Cherenkov emission properly. The most used type of mirror in the current experiments is the aluminum coated one, with a typical reflectivity curve shown in (c) in Figure 2.4. It is also important to have a detector that can operate in this range, and through the curve (e) in Figure 2.4 we can see that the bi-alkali photocatodes fit the requirements.

The curve (f) in Figure 2.4 shows the product between the Cherenkov emission wavelength, its intensity variation with the altitude, the reflectivity of a typical aluminum

mirror and the quantum efficiency of bi-alkali photocatodes. This is the spectrum of observable Cherenkov light with the current technology, showing a peak of emission in 350 nm and a high intensity between 325-400 nm.

Figure 2.4 – (a) Cherenkov emission curve relative to its emission in 250 nm. (b) Emission of the night-sky background relative to 600 nm. (c) Reflectivity of a typical aluminum coated mirror. (d) Transmission of the Cherenkov light from 10 to 2.3 km of altitude. (e) Quantum efficiency of bi-alkali photocatode. (f) Product of (a),(c), (d) and (e) normalized in 350 nm, showing the transmission peak between 350-400 nm that the Cherenkov light is observed.

Source: WEEKES, T. (24).

2.2 Gamma-Ray Astrophysics

The primary purpose of Gamma-Ray Astronomy is to locate and study new sources that emit gamma-ray particles, since they are sparse in the Universe. TeV gamma rays can be generated in three different ways. One is when high-energy accelerated nuclei collide with concentrated gas particles. The flux and energy spectrum of the produced

gamma rays reflects the flux and energy spectrum of its nuclei source. At these energies (GeV-TeV), these charged cosmic rays, usually, do not reach the Earth, and if they do, they have already lost all directional information. High-Energy Gamma-ray Astronomy is the only one able to probe and image the cosmic particle accelerators responsible for the propagation of the high-energy cosmic rays, cooperatively with Radio and X-Ray Astronomy. The other way gamma rays can be generated is through the decay of heavy particles, such as the hypothetical dark matter particles and pions. (25) Therefore, gamma rays might make possible the discovery of the nature and constituents of dark matter. The last way is when electrons are accelerated in the sources and produce energetic gamma-ray particles by inverse Compton scattering. (26)

Until now, supernova explosion shocks is the main possible cosmic ray accelerator, though it is not certain. In order to solve this question, the observation of sources such as Supernova Remnants (SNRs) (27) is important to find out if they truly are cosmic-rays accelerators. The initial expansion velocity of the SNRs is known not to vary too much between sources, which means that only an amplification of its magnetic field could increase the acceleration rate of cosmic rays. The high value of the magnetic field would also eliminate the possibility of a leptonic origin for the observed gamma-ray emission. Thus, an accurate measurement of the intensity of the magnetic field of the SNRs shock is important to disentangle the origin of the observed gamma-ray emission and to gain insights on the way diffusive shock accelerators work.

The acceleration processes (28) can be studied from several kinds of sources. Supernova shockwaves supposedly accelerate different atomic nuclei that generates gamma rays observed in Earth. Pulsar Wind Nebulae (29) generate a steady flow of high energy particles through rotating magnetic fields. Binary systems (30), where black holes or pulsars orbit a massive star, also emit energies of the same order. Because of the elliptical orbit, the particle acceleration and radiation emission are modulated according to the orbital period. Observing these kinds of sources may lead to the discovery of the acceleration processes in different environments, which is not yet certain in modern astrophysics.

To study the possible dark matter (31) particles, which may pair-annihilate and produce gamma rays, the observation of a region with known population of dark matter is necessary. The Galactic Center is a promising region because of its predicted high dark matter density, with a high-energy gamma radiation already found by current experiments. Other sources relevant in the search for dark matter are dwarf spheroidals and dwarf galaxies. These have large mass-to-light ratio, having a low conventional astrophysics background.

Another not fully described phenomena in Astrophysics, which is also a gamma-ray source, are the Gamma-Ray Bursts (GRBs). (32) They are the most powerful explosions in our Universe, and the most known electromagnetic luminous sources. The high luminosity produced by the GRBs makes them detectable up to high redshifts. This allows the Gamma-Ray Bursts to assist in the knowledge of star formation history and reionization of the Universe. GRBs are thought to be powered by ultra-relativistic jets produced by accretion onto a newly formed stellar mass black hole or a rotating highly magnetized neutron star. The difficulty of studying GRBs is to observe the prompt emission before it fades with a wide energy range to capture the spectral energy distribution. No Gamma-Ray Bursts have been observed in energies larger than 100 GeV yet. The observation in these higher energy ranges would enhance the knowledge of the intrinsic spectrum and the particle acceleration mechanism.

There are several other relevant sources for the study of unknown astrophysical processes, but it is not the scope of this dissertation to describe all of them in detail. Therefore, in this section we will give a short summary of the main kinds of sources discovered by current experiments.

2.2.1 Gamma-Ray Sources

Several Gamma Ray Sources (Figure 2.5), both galactic and extragalactic, have been discovered since the beginning of the gamma-ray showers experiments in 1958. In this section we present a summary of the main sources based on Reference (33).

Blazars

Around 1% of galaxies possess an active nucleus, and around 10% of these Active Galactic Nuclei (AGN) release relativistic jets powered by accretion onto a super-massive black hole. When this jet is oriented at an acute angle to the observation line, they are called Blazars, and they have very strong energies and luminosity, making them suitable targets for gamma ray observation. The blazar observations are probes for the study of other physics phenomena, such as the acceleration and propagation of cosmic rays and the formation of axion-like particles. There are over 41 of these sources listed in the TeV catalogs, seen in red in Figure 2.5.

Starburst Galaxies

Figure 2.5 – Map of most recent gamma ray sources discovered. The map is in Galactic coordinates. Several types of sources are shown with different colors according to the Source Types list on the right of the map.

Source: TeVCat (34).

These exhibit a very high star formation rate. Gamma ray emissions are predicted as a result of the interaction of hadronic cosmic rays (abundant in these Galaxies) in the dense gas that forms it. TeV emission have been observed in two of these, M82 and NGC 253, seen in orange in Figure 2.5.

Pulsar

A pulsar is a neutron star that spins emitting a beam of electromagnetic radiation. The Crab Nebula, the closest very high energy gamma ray source in our Galaxy, has a central pulsar. These sources can be seen in yellow in Figure 2.5.

Pulsar Wind Nebulae

This is the most abundant class of known very high energy sources emitters in our Galaxy, seen in pink in Figure 2.5. The shock of accelerated leptons, which produce synchrotron and inverse Compton radiation, are the essential mechanisms for the emission of gamma-rays in these sources. When the nebulae are young, their observation is hard because it is point-like and embedded in their Supernova Remnant parent. At older ages, it expands, making it possible to map their TeV emissions.

Supernova Remnants

They are believed to accelerate particles efficiently at the shock front where the Supernova Remnants (SNR) encounters the surrounding medium. They can be seen in

Figure 2.5 in green. There are two different classes of gamma-ray sources of interest in this class, the actual Super Nova Remnants Shells, based on gamma ray morphology, and sources overlapping with a massive volume of material, such as molecular clouds.

Also, the combined effect of the stellar winds, coupled with several SNR effects, creates an overall wind from the cluster which forms Super-bubbles in the interstellar medium, which accelerates particles with the wind interaction with its medium.

Compact Object Binary Systems

Seen in yellow in Figure 2.5, there are only four confirmed gamma-ray binary systems since 2005. Their emission is believed to come from the accretion (from a black hole) or from a pulsar wind. The four known systems have a neutron star as a compact object.

Globular Cluster

There is a single nearly confirmed Globular Cluster that emits gamma-rays, the Terzan 5, which emission is likely related to the large population of neutron stars in this cluster. This source can be seen in blue in Figure 2.5.

Many of these sources were observed by Imaging Cherenkov Telescopes, that uses the Cherenkov Radiation to locate and analyze sources of gamma-ray particles.

CHAPTER 3

Gamma Ray Experiments

In the 1960s, the Cherenkov light that the gamma ray showers produce proved to be another source of data for new experiments, giving birth to parabolic mirror telescopes with photomultipliers reconstructing the observed image, technique that would later be improved and called as Imaging Atmospheric Cherenkov Telescopes (the main kind of experiment used currently to observe Gamma Ray showers). This technique will be further discussed in Section 3.1. These experiments could observe sources in the TeV range, and the technique is still being improved in worldwide experiments, such as the Cherenkov Telescope Array (Section 3.3), and has several successful active experiments, such as H.E.S.S., VERITAS and MAGIC, which are commented during Section 3.2.

The Imaging Atmospheric Cherenkov Telescopes (IACTs) are the most promising kind of experiment in the TeV energy range. However, another kind of technique complementary to the IACTs is the water Cherenkov experiment. These are composed by a series of water filled tanks in a very large area, detecting Cherenkov light emission through photomultipliers in the bottom of the tanks. HAWC is the newest experiment using this technique, and it will be able to observe events of energies up to 100 TeV. (35)

3.1 Imaging Cherenkov Telescopes

The IACTs are the most used mechanism to observe gamma ray showers currently. These telescopes work through the observation of the Cherenkov light, emitted in a $\sim 1^\circ$ cone in the same direction as the gamma ray source (Figure 3.1). The light is reflected to an array of photomultipliers that reconstructs the shape of the shower, allowing studies of the showers sources, particle kinds and shower direction.

There are two main components of an IACT: the mirror dish and the photomultiplier. The mirror dish reflects the Cherenkov light, which has an emission peak around 350 nm, into the pixels of the photomultiplier. In current experiments the dish is made of several small mirror facets, shaped according to one out of two different layouts:

Figure 3.1 – Cherenkov light cone hitting Imaging Cherenkov Telescopes. The emitted light is contained inside a $\sim 1^\circ$ cone.

Source: H.E.S.S. (36)

- **Davies-Cotton:** (37) All mirror facets have the same focal length f , with the final dish focal length being $2f$. Its disadvantage is a slight temporal dispersion (that increases with the size of the dish), but it has good off-axis imaging.
- **Parabolic:** The focal length of the mirror facets varies according to its position and they are arranged on a paraboloid $z = \frac{r^2}{4f}$. (38) This layout is isochronous, but it has larger aberration for light with a large incident angle.

H.E.S.S. and VERITAS are examples of IACTs with a Davies-Cotton layout, while MAGIC and H.E.S.S. II are parabolic.

Even if the observed source is punctual, its image created by the mirror dish will have a certain size. This size is called as Point Spread Function (PSF), and it must be smaller than the size of the pixel of the photomultiplier used. It is common that the telescopes utilize an array of photomultipliers (PMTs), which usually contains Winston Cones to avoid dead areas in the corners of the PMTs and to reduce noise coming from the environment, increasing their capacity of reconstructing the observed shower.

3.2 Current Experiments

The first generation of Imaging Atmospheric Cherenkov Telescopes had single telescopes installed in a site to observe the Cherenkov light. The Whipple telescope was the first one to succeed in its objective of finding gamma-ray sources, observing gamma-ray emission from the Crab Nebula. Led by this success, a second generation of experiments was proposed, with more than one IACT installed in the same site. These telescopes observed the same air shower, obtaining a stereoscopic view, which led to a more precise reconstruction of the showers. Also, with this kind of observation, Cherenkov flashes from single muons passing near a telescope were more easily removed, lowering the threshold of the IACTs observations and allowing a more precise analysis of the shower directions. This idea culminated in the development of the HEGRA (High Energy Gamma Ray Array) project, that was followed by several other experiments until the present.

In this section we will detail three of the most successful IACTs with stereoscopic view currently: H.E.S.S., VERITAS and MAGIC.

H.E.S.S.

The High Energy Stereoscopic System (H.E.S.S.) has been operating since 2003, in Namibia. It was originally composed by four telescopes with 12 meters of diameter following a Davies-Cotton layout, with the inclusion of a 28 meters diameter telescope, H.E.S.S. II, in 2012 to increase the energy range observed (Figure 3.2).

Figure 3.2 – H.E.S.S. II Telescope Array.

Source: Erlangen Centre for Astroparticle physics. (39)

The smaller telescopes have 60 cm circular mirror facets (because of their smaller cost and optical errors), spherical shaped with focal length of 15 meters, made of glass coated

with aluminum and a protective coating of quartz. (38) Their reflectivities are higher than 80% in the 300 - 600 nm range and their Point Spread Function of 1 mrad diameter. The larger telescope is parabolic, with 36 meters focal length and hexagonal facets of 90 cm each, made of glass coated with aluminum and a quartz protective coating, and different radii according to its position in the full dish. (40)

H.E.S.S. was responsible for the observation of several shell-type Super Nova Remnants, for a survey of the galactic center that revealed more than fifty new Very High Energy Gamma Ray Sources including TeV binary systems and Pulsar Wind Nebulae, for detecting a few Radio Galaxies, such as *Cen A*, Starburst Galaxies (NGC 253, for instance), among others. (41) It is still in operation, and is expected to discover many more events with the recently installed H.E.S.S. II telescope.

VERITAS

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) was built in 2003, with the completion of the four telescopes array in 2007 in Arizona, USA. The four telescopes on their current positions are shown in Image 3.3.

Figure 3.3 – VERITAS site in Arizona.

Source: Science Springs. (42)

The four telescopes have 10 meters of diameter and 12 meters of focal length in a Davies-Cotton layout. The mirror facets are hexagonally shaped, spherical, with 60 cm flat-to-flat, made of aluminized glass and anodized. (43)

Among the discoveries of VERITAS are the detection of pulsed gamma-ray emissions between 100 GeV up to 400 GeV in the Crab Nebula, a binary system with a very long period in a joint campaign with H.E.S.S., radio flares emitted from Radio Galaxies and new Starburst Galaxies as sources. (41) The telescopes passed through an upgrade in 2009 to lower the energy threshold, changing the position of one of the telescopes. (44)

MAGIC

The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes) teles-

cope was first built in 2003 in La Palma, Canary Islands, with a large Cherenkov Telescope of 236 m^2 . In 2009 a second similar telescope was installed, being called MAGIC-II, which allows observations with a threshold of 25 GeV, the lowest one of the current observatories. Both telescopes can be observed in Figure 3.4.

Figure 3.4 – MAGIC telescopes in La Palma.

Source: MAGIC picture gallery. (45)

MAGIC uses a parabolic layout on both of the 17 meters diameter telescopes. Over a thousand square mirror facets of either $49.5 \times 49.5 \text{ cm}$ or $99 \times 99 \text{ cm}$ cover the telescopes, all spherical with different focal lengths for each position in the dish, made of an aluminium plate, diamond milled to achieve the spherical and reflective surface, and a quartz coating for protection. (46)

The telescopes have observed sub-100 GeV pulsed emissions from the Crab Nebula, as well as from 100 GeV to 400 GeV along with VERITAS; the observation of very high gamma-ray flux variability of a blazar; the survey of the Perseus galaxy cluster, from where the experiment obtained some new gamma-ray sources in the TeV range, among others.

As we can see through the content of this session, the current IACTs experiments have been very successful in discovering new sources and in observing astrophysical phenomena. However, most of them are complementary in their energy thresholds and ranges, as we can see in Figure 3.5, confirming each other results through repeating measurements. Increasing the energy range is necessary to gather more data about not currently observable phenomena of the Universe, which led to the proposal of the Cherenkov Telescope Array, detailed in the next section.

Figure 3.5 – Integral sensitivity of current experiments (50 h for IACTs and 1 year for FERMI-LAT and HAWC) and predicted sensitivity for CTA.

Source: ACHARYA, B. (47).

3.3 Cherenkov Telescope Array - CTA

The Cherenkov Telescope Array (47) was proposed in 2006 to the European Strategy Forum on Research Infrastructures as a research infrastructure for gamma-ray astronomy. It will be the next generation of Imaging Atmospheric Cherenkov Telescopes, with an increase of sensitivity in relation to modern experiments by one order of magnitude (from a few tens of GeV up to 100 TeV), as well as better angular and energy resolutions. There are over 1000 researchers from 27 different countries working on the development of the Observatory, which is predicted to begin construction in 2016.

In order to have a full-sky coverage, CTA will consist of two sites, one in the northern hemisphere and one in the southern one, with 50-100 telescopes of three different sizes in each of them. This high number of telescopes will be responsible for the increase by one order magnitude of its energy coverage and sensitivity. The improvement on the energy range may result in new discoveries of gamma-ray sources and the investigation of phenomena not yet observed (such as dark matter). CTA will also be the first ground-based gamma-ray experiment operated as an open observatory, allowing many scientists to use its data to develop new theories and discover new physics.

Through the next sections we discuss the CTA concept and the decision of its location in the southern hemisphere.

3.3.1 Concept

CTA aims to make new discoveries in several different areas. It is planned to study cosmic-ray acceleration and propagation through the observation of new sources, gamma-ray emission processes, among several others. In order to observe all these phenomena, which have different energy ranges, it becomes necessary the use of different kinds of telescopes to increase the sensitivity of the current experiments. Therefore, the observatory must operate in three different energy ranges:

- **High energy range (>10 TeV):** The main difficulty in this range is the quantity of observed events. It is necessary to have a large array with a high number of telescopes spread out in a large area. Small Size Telescopes (SST), with spacing of 100-200 meters between them (which is the size of the Cherenkov Light pool), are proposed to observe in this energy range.
- **Core energy range (0.1-10 TeV):** This is the energy range in which the current experiments operate, and the same technology of Middle Size Telescopes (MSTs) of the ongoing experiments is going to be used in CTA. The increase of sensitivity in this range will be achieved by an increase in the number of MSTs in the Observatory, having a larger area of observation than the existent experiments.
- **Low energy range (≤ 100 GeV):** In this range the events are numerous, therefore it is only necessary to have a small area in the array. Closely placed Large Size Telescopes (LST) in small numbers (≤ 4) are proposed to observe in this range.

The basic concept for the CTA Observatory can be seen in Figure 3.6.

As mentioned earlier, there will be three different sizes of telescopes built in CTA, of small, medium and large size to observe in three different energy ranges. There are several different designs proposed for each of them, but we will focus in showing the ones more likely to be approved by the Consortium.

Large Size Telescope (LSTs)

There will be four or less of this kind of telescope concentrated in a small area to observe the low energy range. They will have 23 meters of diameter, with the design similar to the MAGIC telescopes, but with smaller weight (through the use of carbon fiber tubes in its structure) and more modern materials in order to lower the costs of construction and maintenance. We can see a blueprint of this design in Figure 3.7.

Figure 3.6 – CTA concept art.

Source: Deutsches Elektronen-Synchrotron. (48)

The primary objective of the LSTs is to quickly move in case of a Gamma Ray Burst alert, and to do that the materials must have a lightweight structure and a fast response in the electronics of the telescope base.

The 23 meters reflector of the LST will consist of hexagonal mirror facets with ~ 1.5 meters flat to flat. The profile of the large reflector will be parabolic, with each mirror facet being spherical with different focal lengths depending on its position on the dish. The focal length will be of 28 meters, therefore each facet will have their focal lengths between 28 and 29.2 meters.

The LSTs facets and the mechanical structure are being prototyped mainly in Japan.

Figure 3.7 – LST design blueprint.

Source: CARR, J. et al. (49).

Medium-Sized Telescopes (MSTs)

This is the size of most of the current Imaging Cherenkov Telescopes experiments, having a well studied and known technology for its fabrication. The model of this telescope proposed for CTA is a mixture between H.E.S.S. and VERITAS designs, a ~ 12 meter Davies-Cotton reflector. It will have a focal length of around 16 meters and a pixel size of the camera of 0.18° (which is the best cost/effectiveness ratio for the camera). One prototype of this model was built in DESY, Berlin, Germany, observed in Figure 3.8(b), along its prototype design in Figure 3.8(a).

Figure 3.8 – Medium-Sized Telescope (a) design and (b) prototype built in DESY, Berlin, Germany.

Sources: (a) ACHARYA, B. (47) and (b) Deutsches Elektronen-Synchrotron (50).

The mirror facets of these telescopes will be hexagonal with 1.2 meters flat to flat, spherical, with a single focal length of 16 meters (the same as the full sized reflector, as proposed in the Davies-Cotton design). There are several mirror facets technologies proposed for the MSTs from France, Poland and Italy mainly, which are being tested and compared to choose the most cost/effective one before the beginning of the Observatory construction.

Small-Sized Telescopes (SSTs)

These will be the telescopes used to observe high energy events of the sky, therefore it is necessary that they exist in large number and that several of them observe the same event. In order to do that, they must have the lowest cost as possible, and a mirror diameter of ~ 4 meters for the trigger threshold of 1 TeV. There are two types being proposed for the Small Telescope, the SST-1M, that has only one reflector of 4 meters diameter, and the SST-2M, with two reflectors and a less costly PMT camera.

The SST-1M is being prototyped by the Swiss and Polish groups. It is a Davies-Cottons optics telescope with a focal length of 5.6 meters and it will use an hexagonal silicon photomultiplier with a Winston Cone to increase its collective area to ~ 20 m². Its mirror facets will have 0.58 meters flat-to-flat with a curvature radius of 11.2 meters. A prototype was built in June/2014, as seen in Figure 3.9.

Figure 3.9 – SST-1M prototype built at the test site near the Institute of Nuclear Physics Polish Academy of Sciences .

Source: AGILE science app. (51)

The SST-2M model is being proposed by the ASTRI (Italy) and the GATE (France) groups, with the first ASTRI prototype inaugurated in October/2014. It enables a good angular resolution of around 10° and it allows the reduction of the focal length and, in consequence, both the pixel and camera size. It will have 4 meters diameter as the SST-1M model, with 3 meters distance to the second reflector. The main mirror facets will be hexagonal, with 85 cm flat-to-flat, being 18 facets per large reflector, according to the version proposed by ASTRI, and the secondary mirror will be circular with 1.8 meter diameter. A prototype of this SST was already built, and it can be seen in Figure 3.10.

CTA is now in the prototyping phase, in which at least one model of each telescope size is being built and tested in order to demonstrate its efficiency and quality for the final construction. However, before the beginning of the construction phase, it is necessary to choose the Observatory site in the southern hemisphere, detailed in the next section.

Figure 3.10 – SST-2M prototype built by the ASTRI group at Serra la Nave, Italy.

Source: By the author.

3.4 Sites for CTA

In order to decide where CTA is going to be built in the southern hemisphere several requirements were proposed. (52) The latitude of the site must be between -40° to -20° , with altitudes of 1500-2500 meters and an usable area of more than 10 km^2 . The largest temperature variation that all equipments must work properly is from -20 to $+40^\circ\text{C}$. The sky must be clear during most of the year, with minimum cloud cover and ambient light, and the site must have easy access and good local infrastructure.

In the southern hemisphere the first proposed sites were located in Argentina, Namibia and Chile, and in the northern one on the Canary Islands, Mexico, Arizona, China and India (Figure 3.11).

Since our work is mostly realized in the Argentinian site of San Antonio de los Cobres, we will further describe it in the next section, afterwards comparing it to the other proposed sites in the southern hemisphere.

3.4.1 Argentinian sites

Two main sites were selected to be proposed to CTA, El Leoncito, in San Juan, and San Antonio de los Cobres (SAC), in Salta. Leoncito is located at 2660 meters above sea level, while SAC is at 3600 meters above sea level.

Figure 3.11 – First proposed sites for CTA construction in the northern and southern hemispheres. In the northern there are proposed sites in the Canary Islands, Mexico, Arizona, China and India, while in the southern there are proposed sites in Chile, Argentina and Namibia.

Source: ACHARYA, B. (47).

El Leoncito has more than the 10 km^2 of flat area required by the Consortium for the construction of the telescopes. It is located inside the El Leoncito National Park, which is an astronomical reserve created to keep the sky clear with little background from artificial lights. There are three main cities near to the site, El Barreal (30 km distance), San Juan (350 km) and Mendoza (300 km).

The temperature at Leoncito varies, at most, from -10 to 30°C , which is within the -20 to 40°C limit range. The largest wind velocity is below 40 km/h , which is the observation limit considered for CTA. The sky is completely clear during 78% of the year, but the observational time is around 80% considering partial sky-covering.

The San Antonio de los Cobres site also have more than 10 km^2 of flat area, surrounded by hills hundreds of meters higher than the plateau. It is located 22 km north of the city of San Antonio de los Cobres and 200 km away from Salta, the capital of the region.

The area has a semi-arid climate, with large variations of temperature during the day. During the night, the temperature varies from $\sim -7^\circ\text{C}$ to 20°C , which is within the temperature variation requirements, and during the whole day it varies from -10°C to 30°C at most. There is more wind in SAC than in Leoncito, with the higher speed of 50 km/h . The humidity is lower than 90%, according to the requirements, during 96% of the year. The cloud coverage of this region is $\sim 20\%$, a little higher than in the Leoncito site.

The main problem to be analyzed in the San Antonio de los Cobres site, where our experiments took place (Chapter 4), is the condensation time of the mirrors. This

phenomenon is supposed to happen more in this site because of the sudden temperature variations that are smoother in the other proposed sites.

3.4.2 Comparing the sites

There are three other sites proposed in the southern hemisphere, two in Namibia and one in Chile.

Namibian sites: There are two proposed sites in Namibia, called *Aar* and *H.E.S.S.*. *Aar* is the one being strongly investigated, since *H.E.S.S.*' characteristics are already well known because of the *H.E.S.S.* telescopes installed there. The site is located at 1633 meters above sea level, near to the Kubub plateau. The area available for the construction of the Observatory is larger than the 10 km² required by the Consortium in both sites.

The cloud coverage of the sky is $\sim 20\%$. The wind during the night hours was below 36 km/h during 99% of the time, and no gusts above 200 km/h were detected. The temperature was between -5 and 35°C in both sites, which is within the requirements of -20 to 40°C. The time loss because of high humidity during clear nights was of 2%.

Aar has no night sky background because of artificial lights, being shielded from roads and the nearest city of Aus. *H.E.S.S.*, however, might have some background effects from the city of Windhoek in the north-east. The most intense source of night sky background is the brightness of the Milky Way, clearly observed with naked eyes in both sites.

Chilean site: The Armazones site proposed in Chile is located at 2500 meters above sea level. The available area for the construction of the telescope is of hundreds of km², much larger than the 10 km² required by the Consortium. The closest major city Antofagasta is 120 km away and its light pollution is negligible at the site location. Rain occurs less than 1% of the year, and snowing is extremely rare and evaporates in a few hours. The minimum temperature observed was of -10°C and the maximum 22°C, both within the Consortium requirements. The cloud covering of the sky is lower than 10%, which provides an observational time of, at least, 90% of the nights, which is the highest in the proposed sites.

Table 3.1 compares all sites cloud covering of the sky, which is one of the most important characteristics of the observatory. It is noticeable that the sky covering in the Chilean site of Armazones is much lower than the others.

Table 3.1 – Percentage of cloudless nights for each southern site. The table relates each site with its percentage of time with a clear sky, with less than 20% of clouds covering it.

Sites	% time cloud fraction <20%
SAC	74
Leoncito	82
Armazones	90
HESS	78
Aar	82

Source: BULIK, T. (16)

The time lost because of bad weather conditions for each site is shown in Table 3.2. It is smaller in the Leoncito site, and larger in Armazones.

Table 3.2 – Lost observational time because of bad weather conditions for all southern sites. The table shows loss because of strong wind, too low or too high temperatura and high relative humidity for each southern proposed site.

Sites	Wind >36 km/h	Ambient temperature <-15°C or >25°C	High relative humidity	Total
SAC	0.8	0	0.5	0.9
Leoncito	0.2	0	0.3	0.5
Armazones	8.9	0	0	8.9
HESS	0	0.7	0.5	1.2
Aar	1.4	0.6	1.3	3.1

Source: BULIK, T. (16)

It is clear that all of the proposed sites are similar in their climates and heights. Therefore, to choose the location of CTA other characteristics are being analysed, such as the infrastructure available, energy generation conditions and political support in the region. Currently, there are two high priority sites in the southern hemisphere: Aar, in Namibia, and Armazones, in Chile, and Leoncito is being kept as a reserve option.

3.5 Mirrors for CTA

Mirrors developed for Cherenkov telescopes are different from the optical ones in several aspects. First, they are composed of several mirrors smaller than the full reflector size, which makes the fabrication easier and with a lower cost than the large mirror optical ones. Their Point Spread Function (PSF) can also be larger than it is on the optical mirrors, of a few arcmin per mirror. IACTs are not covered with a dome, therefore the

mirror facets are always exposed to the environment with no mechanical protection. This makes it necessary to have a protective coating over the reflective layer of the facets, which is another challenge in the construction of cost/effective mirrors.

Since each telescope from CTA will need around 400 m² of mirrors, the development of new technologies for the mirror facets is necessary. These facets should provide highly reflectivity in the Cherenkov emission range (300-550 nm), average optical properties and small cost. In the next sections we will explore the requirements to create the mirror facets for CTA, as well as the current proposals of the facets manufacturing.

3.5.1 Mechanical and optical requirements

The basic specifications of the CTA mirrors have been proposed at first in 2009 (53) and they were updated in the following years. (54) The shape of the mirror facets will be hexagonal, with 1-2 m² of area each. Since the mirrors will vary from 40° up to 90° of elevation, the facets must be very rigid to endure gravity deformation without changing its optical characteristics. The mirrors should not suffer mechanical deformation during the expected 10 years of operation of the Observatory.

CTA will be placed in altitudes between 1000 and 3000 meters, where the temperature variation is very large. The facets should resist to this variation with no deformations between -15°C and 25°C. They will most likely be spherical for the Medium-Sized Telescopes and the Small-Size Telescopes because both will follow the Davies-Cotton layout, and aspherical (different radii in perpendicular directions) for the Large-Size Telescopes, of a parabolic design.

There are two main optical properties each mirror facet possess. The Point Spread Function (PSF) is the size of the image formed by the mirrors in the photomultiplier (PMT) camera observing it. For IACTs, the PSF have no need to be smaller than half of the pixel size of the PMT, which is usually larger than 5 arcmin. The reflectivity gives the percentage of the incident light that is returned by the mirror through its imaging. It should be optimized between 300 and 450 nm, with more than 85% reflectivity in the 300 - 550 nm wavelength range.

Current experiments use aluminum as their reflective coating, with protective layers on the top of it. These mirrors usually lose 4-5% of their reflectance per year of observation, which requires re-coating every 5 years. Since CTA will consist of over 1000 mirrors,

this process is not viable for the 10 years exposure predicted. This provides the biggest challenge in the manufacture of the mirrors, which is keeping all optical and mechanical properties stable during the 10 operational years of CTA.

3.5.2 Mirror construction techniques

Several Institutes are developing techniques to build the mirror facets for CTA. The glass replica is the most used one currently, being manufactured by the groups of INAF Brera (Italy), CEA Saclay (France), ICRR (Japan) and IFJ-PAN (Poland) with local industry partners. The concept of this method is to form a thin sheet of glass on a very precise mold that gives the exact curvature of the mirror and then gluing a structural material and another glass sheet in the back to create a rigid sandwich structure. Each of the groups that are currently producing this kind of mirrors have a different component, and we will describe them during this Section.

INAF Brera model: A thin glass is cold-slumped on a spherical mold. This glass is then glued to an aluminium honeycomb and a back sheet through an aeronautical glue. This process is describe in Figure 3.12. The spherical substrate is then evaporatively coated with aluminium and a protective coating of three layers (SiO_2 , HfO_2 and SiO_2), from 120 up to 240 nm thickness. These mirrors are light, with ~ 15 kg and very rigid.

Figure 3.12 – Cold slumped glass technique from INAF Brera. The Master is the precise spherical mold used to shape the front glass sheet. The Al honeycomb substrate is also shaped according to the glass sheet and is used to give a stronger mechanical resistance to the mirror. Then a back glass sheet is glued to provide better support and avoid changes to the shape because of thermal expansion.

Source: FÖERSTER, A. (54).

CEA Saclay model: (55) A similar technique to the INAF mirror is applied by this group. First, a glass fiber sheet is glued to an aluminium honeycomb and another

glass sheet. These are cold-slumped against a spherical mold, obtaining a spherical shell. Then, two glass sheets are glued to each face of the shell. This is shown in Figure 3.13. Different kinds of glues were tested, but the one with the better results was a temperature polymerized Araldite resin. The symmetric front-back is important to keep the focal distance constant, since both suffer the same modifications with temperature. The mirror weighs 25 kg.

The coating of the mirrors are made by Kerdry Thin Film Technologies through an evaporation technique. The mirror is coated with aluminium and three protective layers of SiO_2 , HfO_2 and SiO_2 .

Figure 3.13 – Cold slumped technique from CEA Saclay. It adds a G10 sheet between the glasses and the Al honeycomb to provide a better mechanical resistance. The shaping of these structures follows the same procedure as the INAF Brera prototype.

Source: BRUN, P. (55).

ICRR Japan model: The same cold-slumped technique is being used in hexagonal 1.5 meters flat-to-flat as planned for the LSTs. They are consisted of two glass sheets with an aluminium honeycomb between them. The coating is a mixture of Cr with Al with a triple protective layer of SiO_2 , HfO_2 and SiO_2 .

IFJ-PAN model: (56) It is a rigid sandwich made of two flat glass panels separated by v-shape aluminium spacers, glued together by an epoxy resin. Then, a spherical layer of epoxy resin is formed in the front panel using a mold. On the top of this resin a Borofloat glass sheet is glued to it using the same mold. This last glass sheet is previously coated with Al and has a SiO_2 protective layer. In order to improve resistance to mechanical impacts, two glass fibre reinforcements are placed between the spherical and the flat layers. We can see the model in Figure 3.14. This mirror weighs 45 kg.

All the mentioned mirrors use an Al coating with protective layers on the top of it, either with a single layer of SiO_2 or with a triple layer of SiO_2 , HfO_2 and SiO_2 . The evaporative technique does not heat the substrate receiving the aluminium coating, which avoids changes in its shape and curvature. However, the reflectivity of these coatings

Figure 3.14 – Composite mirror technique from IFJ-PAN. It adds two spherical epoxy resin layer to the front and back glass + glass fibre sheets to increase mechanical resistance in relation to the previously shown prototypes.

Source: DYRDA, M. (56).

are at most 90% above 300 nm and it varies greatly when exposed to environmental conditions. In order to increase the duration of the reflective coating as well as the reflectivity percentage, it was proposed the use of dielectrical coatings for the CTA mirrors. A comparison between the reflectivity for the three investigated mirror coatings is shown in Figure 3.15.

Figure 3.15 – Reflectivity comparison between four mirror types. In black, the reflectivity of the Al with a single layer of SiO_2 is shown. In red, the Al with three protective layers. In green the dielectric mirror with a cut in 600 nm and in blue with a cut in 550 nm. It is clear that the dielectric mirrors have larger reflectivity values than the aluminum ones.

Source: FÖRSTER, A. (57).

Dielectrical coatings use interference of several material layers of different refraction index to achieve high reflectivity at a specific wavelength range. Since the observable Cherenkov light emission peak is between 300 and 550 nm, this kind of coating would

provide over 95% of reflectivity in this range through coating two different materials. The difficulty of this kind of coating is the technology available to obtain homogeneous thickness over large surfaces (1.2 meters flat-to-flat in the hexagonal mirrors for the MSTs), which is being currently developed.

The biggest advantage of dielectrical coatings is their durability. In Figure 3.16, the Al mirrors with one and three protective layers, as well as a dielectrical coated mirror, were exposed to temperature cycles from -10°C up to 60°C and humidity cycles from 5% up to 95% during 8000 hours. It is clear that the dielectric mirror has a smaller difference on its reflectivity than the Al mirrors, demonstrating its longer durability. However, dielectrical coatings are easier to condense (58) than Al with the triple protective coatings, which decreases the observational time in the Observatory. In order to solve this problem, a coating of a high reflective layer in the infra-red region below the dielectrical layers was suggested, which would hold the heat to avoid condensation in the layers, and is currently being tested.

Figure 3.16 – Reflectivity comparison between three mirror types. In black, the reflectivity of the Al with a single protective layer before (full) and after (dashed) the temperature and humidity cycles. In red, the reflectivity of the Al with a triple protective layer, and in blue, of the dielectrical coated mirror. It is clear that the dielectric mirror had less variation on its reflectivity after the cycles than the aluminum ones.

Source: FÖRSTER, A. (57).

CHAPTER 4

Development of a Mirror Test Facility

In this chapter, we discuss the development of a facility to test mirrors in working conditions at the operational site. The test facility was installed in San Antonio de los Cobres (SAC), Argentina. Our study had two aims. First we wanted to compare the performance and characteristics of several mirror facets constructed by manufacturers around the world. Second, we intended to show that SAC was a suitable site to construct CTA in the Southern hemisphere.

In this facility we took three different measurements to test the quality of both the mirrors and the site itself: the mirrors focal positions, obtained through a 2f system; (55) the reflectivities of the mirror surfaces; and the period of condensation of each mirror facet. The tests will be detailed along this chapter.

4.1 Mirror Test Facility

The development of the Mirror Test Facility (59) in the city of San Antonio de los Cobres, Salta, Argentina was performed with the collaboration of the groups of La Plata (Argentinian Institute of Radio Astronomy - IAR) and Mendoza (Comission of Atomic Energy - CNEA), both from Argentina.

In the facility, different mirrors were exposed during two periods of time: From May/2013 until October/2013, and from December/2013 until June/2014. In the first period there were two mirrors exposed, both manufactured at the Commissariat of Energie Atomique, Saclay, France, made of Glass/Aluminum, and during the second period, there were four: three made of Glass/Aluminum, from France, Poland and Italy, and one made of Glass/Dielectric, used in the construction of the HESS telescope. Both constructions can be seen in Figure 4.1.

There was also another mirror exposed made by the brazilian company Opto Electronics. It was a square 50x50 cm Glass/Aluminium mirror, with its structure built by

the Commissariat of Energie Atomique, France, and the coating by Opto Electronics, São Carlos, Brasil. This mirror had been exposed to environmental conditions at the city of São Carlos for more than one year before being moved to San Antonio de Los Cobres in order to test its coating mechanical and reflective resistance. It can be seen in Figure 4.1(c).

Figure 4.1 – Mirror Test Facility during its two time periods, with (a) 2 mirrors and (b) 4 mirrors, and (c) the mirror from Opto Electronics.

(a)

(b)

(c)

Source: By the author.

The mirrors supports allow them to move between two positions: looking downwards during the day (to avoid causing fires in its focal position and to not scare the local fauna) and looking upwards to the sky during the night (which will be its working position in the telescope). Above them, LED stripes were installed to illuminate the mirrors tangentially to their surfaces to increase scattering effects, allowing night observation of the mirrors. Webcams looking frontally to the mirrors (Figure 4.2) took pictures every 10 minutes automatically and sent them to a server from where we could download them in the next day.

Figure 4.2 – All constituents of the MTF. The LED stripe illuminates the mirror surface that is then observed by the web-cam. The support allows the mirror to move between two positions, turned up or down. The web-cam takes pictures every ten minutes during the night remotely.

Source: Courtesy of Beatriz García.

4.2 $2f$ system measurements

Two of the main characteristics of a mirror are its focal position and its Point Spread Function. Through this experiment, we analysed variations of these parameters as a consequence of the environmental conditions the mirrors were exposed to.

The blueprint of the equipment can be seen in Figure 4.3. The parts necessary for its construction are a tripod for the support, a LED punctual source and a white screen to observe the image formed by the mirror.

For the superior part, we used an aluminium plate, with 40 cm long and 20 cm width. The high power LED and its circuit must be put on it, as well as a white screen to capture the image. The screen was a common white painting screen, of 20 x 20 cm, with a graph paper on its surface with the smallest division of 0.1 cm. This allowed us to measure the spot size through pictures. The plate setup can be seen in Figure 4.4.

Figure 4.3 – Blueprint of the 2f system. Its is composed of a 20 x 20 cm screen, a high power LED and an adjustable height tripod.

Source: MEDINA, C. (59)

Figure 4.4 – Superior part of the 2f system assembled, with the screen, LED and the laser measurer in position.

Source: By the author.

The punctual source was a blue LED, of 3 W power. It is possible to provide energy to it through a common 6 V battery using a simple circuit, shown in Figure 4.5(a). The components of the circuit were a variable resistor to control the LED intensity, a low value resistor to avoid burning the diode, a switch and a support for the battery connection. This circuit was placed inside a box to avoid damage caused by dirt and wind. The LED was also protected through a small square box and had a lens to collimate its light, as well as a long tube around it to assist in the light guiding. The final version is shown in Figure 4.5(b).

Figure 4.5 – LED circuit (a) before being complete and (b) fully installed in the 2f system.

Source: By the author.

The distance between our equipment and the mirror had to be acquired in order to measure the focal distance. For this task, we used a laser distance measurer because of its high precision (0.001 m) until 50 meters distances. The laser was pointed to the 2f system from the mirror surface.

A commercial tripod was bought for the system support. Its height could vary from 70 to 210 cm. Another tripod was attached directly to the aluminium plate to place the camera, ensuring that the pictures were taken from the same distance. The final setup is shown in Figure 4.6.

Figure 4.6 – 2f system final version.

Source: By the author.

The mirror facets in the MTF were concave with their focal positions around 16 meters. Because of the spherical mirrors properties, at twice the focal distance the image made by the mirror must have the same size as the illumination source (Figure 4.7). Through the observation of this image size the size of the Point Spread Function (considering the source as punctual) can be obtained. Varying the distance of the source from the mirror, the position where the image is the smallest is the $2f$ distance. These conditions allow us to find both of the parameters we are looking for with a single equipment.

Figure 4.7 – Theoretical operation of the $2f$ system with a punctual source. The source illuminates the concave mirror, that focus the light at a $2f$ distance from its surface.

Source: Courtesy of Clementina Medina.

A high power LED emits a punctual collimated light that illuminates the entire mirror surface. The mirror reflects it directly to a white screen installed a few centimeters away from the source. With this configuration we have approximately a retroreflection, providing us with an image without aberrations. This image is not punctual because of imperfections on the mirror surface. As the theoretical position of the focal distance is known, we move the equipment for 4 to 5 meters around twice this value, observing the image formed on the screen. Pictures are taken by a standard digital camera every 50 cm of distance. The closer the equipment is from the $2f$ position of the mirror, the smaller the image will be, increasing again as it goes farther from it. This allows us to find the real value of the focal distance of the mirror and its Point Spread Function.

4.3 Reflectivity measurements

One of the most popular instruments used to measure reflectivity is the spectrometer. We used an Ocean Optics[®] spectrometer of the Jaz[®] model (Figure 4.8). Jaz[®] is a portable spectrometer with a pulsed Xenon lamp (that emits light between 300 and 800 nm) that is sent through an optical fiber to the mirror surface. It is then reflected back

through another optical fiber to the spectrometer, protected by a metal tube. The reflected light then hits a diffraction net that allows the observation of the reflected spectral lines. The spectrum is turned into graphics that can be seen through the SpectraSuite[®] program, provided by Ocean Optics[®].

Figure 4.8 – Superior part of the Jaz spectrometer, where we can see the main panel and the metallic tube where the optical fibers are located.

Source: By the author.

Before we started to use this equipment we had to do a calibration of the wavelength observed by the spectrometer. This procedure is made through the comparison between the spectrum of a known source (with known emission wavelengths), and the spectrum observed in the SpectraSuite[®] program. Through the difference between the two observed wavelengths it is possible to find the coefficients for the spectrometer wavelength equation, which is added to the core programming of the equipment. This calibration might be often necessary, therefore the calibration lamp must be portable and usable anywhere. We developed a simple neon lamp (Figure 4.9(a)) connected with a 100 k Ω resistor that can be directly connected into a 220 V plug. We chose this lamp due to its well known emission peaks, seen in Figure 4.9(b).

We could elaborate a table through this graphic and the one observed in the SpectraSuite[®] program to do a linear regression process to solve the wavelength equation (61),

$$\lambda_p = I + C_1 p + C_2 p^2 + C_3 p^3, \quad (4.1)$$

where λ_p is the wavelength of the chosen peak, p is the real wavelength of the peak and C_1, C_2, C_3, I are the correction coefficients. The regression process was made au-

Figure 4.9 – (a) Neon lamp and (b) its emission spectrum.

Source: (a) By the author and (b) Astronomy amateur (60).

tomatically through a data analysis program and the peaks were checked manually after the calculation, giving us a precision of ± 5 nm.

In order to ensure the external light would not affect our measurements, a black head was put on the top of the tube where the optical fibers are located. Since the external part of the head has a rubber band, it can touch the mirror surface, isolating the sample from external light. Furthermore, a dark and a reference spectrum must be taken before each measurement. The former is done by putting our reference mirror over the head with the Xenon lamp turned off (ensuring that no external light is interfering with our measurement), and the latter with the lamp turned on (providing the real reflectivity of the substrate). After obtaining these spectra, we proceeded to measure the mirror, as shown in Figure 4.10.

The reference spectrum taken at the beginning of the measurement must always be the same, therefore a reference mirror with a known reflectivity spectrum was necessary. We used an aluminium coated one made at the Instituto de Física de São Carlos (IFSC) - USP, Brazil. Its nominal reflectivity can be observed in Figure 4.11.

We took reflectivity measurements of the four mirrors installed during the second period of the experiment, as well as of the mirror we developed with Opto Electronics. The aim of these measurements is to analyse the quality of the aluminium substrate by the reflectivity variation with the environmental conditions of the proposed site.

Figure 4.10 – Mirror being measured with the Jaz[®] spectrometer, with immediate observation of the graphics through SpectraSuite[®].

Source: By the author.

Figure 4.11 – IFSC reference mirror reflectivity spectrum used during all measurements.

Source: By the author.

The reflectivity obtained by our spectrometer is local because the optical fibers are approximately punctual compared to the size of the mirror facets (1.2 meters). In order to obtain an estimative of the global reflectivity of the mirror surface we took local reflectivity measurements in twelve points around the hexagonal mirrors and in ten points around the circular one, such as shown in Figure 4.12. The final reflectivity is obtained by taking the average between these measurements.

Figure 4.12 – Approximate positions of the reflectivity measurements for the (a) hexagonal and (b) circular mirrors. These could not be taken in the center of the mirrors because of the positioning of the sensors in their surfaces.

Source: By the author.

4.4 Condensation measurements

The pictures taken automatically by the webcams are the resources utilized to identify when the mirror surfaces condensed during the night. There were different numbers of pictures for each of the five mirrors observed at our MTF, as seen in Table 4.1.

Table 4.1 – Number of pictures and observation periods of the mirrors at the MTF.

Origin	Type	Name	Initial date	Final date	Number of days	Number of pictures
Poland	Glass/Aluminium	I	—	—	—	—
Italy	Glass/Aluminium	II	25/12/2013	06/04/2014	103	6116
HESSII	Glass/Dielectric	III	25/12/2013	06/04/2014	103	6192
France	Glass/Aluminium	IV	09/05/2013	18/10/2013	148	6200
France	Glass/Aluminium	IV	25/12/2013	06/04/2014	103	6002
France	Glass/Aluminium	V	09/05/2013	18/10/2013	148	6205

Source: By the author.

The mirror from Poland was too heavy and its support stopped working during the second day of exposure, not allowing it to be analysed.

One example of the pictures taken by the webcams is shown in Figure 4.13. In the next chapter we will describe their preparation for analysis and the acquisition of parameters related with condensation from them.

Figure 4.13 – Mirror IV picture taken by the webcam.

Source: By the author, courtesy of the Argentinian group.

CHAPTER 5

Data analysis of the Mirror Test

Facility mirror measurements

In this chapter the analysis of the data acquired by the methodology described in chapter 4 will be shown. In session 5.1 the 2f and PSF analysis will be made. In session 5.2, a comparison between the reflectivity in December-2013 and June-2014 will be presented, and in session 5.3, the picture analysis to calculate the total condensed time of the mirrors will be exposed.

5.1 Variation of focal position

The measurements were taken during two visits to the facility: November/2013 and December/2013. In the first visit there were three mirrors exposed and in the last one, four. Therefore, we have different quantities of pictures for each observed mirror. The pictures were taken from 30 to 34 meters distances from the mirrors, with 0.5 meters between them.

The CTA Consortium have a requirement for the PSF size of the Middle Size Telescope Mirrors (15) that must be acquired for the mirror to be accepted as a prototype. That requirement is that 80% of the light must be contained inside a 0.18° angle around the spot center, considered the size of the PMT camera that will collect the reflected light.

The results will be presented for each mirror separately, with their names following the ones listed in Table 4.1.

5.1.1 Mirror I

It was only possible to make one measurement of this mirror, in December/2013, when it was installed at the MTF. Its pictures are shown in Appendix A, section A.1, and the data are shown in Figure 5.1.

There is not enough data to compare the PSF size according to the time the mirror was exposed. It is possible to know that its focal position is at 16.25 ± 0.01 m, since that is the position where the image is the smallest. The angle at the operating distance $2f$ can be calculated through

$$\tan(\theta) = \frac{\frac{PSF}{2}}{2f} \quad (5.1)$$

Figure 5.1 – Data of the PSF size versus the distance measured for the Glass/Aluminium Mirror I. The smallest PSF point shows its $2f$ position.

Source: By the author.

For the Mirror I all the observable reflected light is inside a $\theta = 0.018 \pm 0.001^\circ$ circle, meeting the proposed requirement.

5.1.2 Mirror II

We took two measurements of this mirror, in November/2013 and in December/2013. The pictures taken are in Appendix A, section A.2, and the analysed data are shown in Figure 5.2.

The Mirror II focal position is 16.50 ± 0.01 meters in both measurements. Its PSF in November/2013 was $\theta = 0.026 \pm 0.005^\circ$ and in December/2013 was $\theta = 0.021 \pm 0.001^\circ$, both within the requirements. The small variation between the PSF size means that the shape of the mirror changed because of the environmental conditions it was exposed to.

5.1.3 Mirror III

This mirror was measured in November/2013 and in December/2013, with pictures shown in the Appendix A, session A.3. The data taken is shown in Figure 5.3.

The focal position of the Mirror III is located at 15.4 ± 0.2 meters in both measurements, which was the expected value. Its PSF size in November and December was $\theta = 0.032 \pm 0.001^\circ$, acceptable within the requirements and constant. Therefore, the Mirror III suffered no changes in its shape during its exposure to the environment.

Figure 5.2 – Data of the PSF size versus the distance measured for the Glass/Aluminium Mirror II. The smallest PSF point shows its 2f position.

Source: By the author.

Figure 5.3 – Data of the PSF size versus the distance measured for the Glass/Dielectric Mirror III. The smallest PSF point shows its 2f position.

Source: By the author.

5.1.4 Mirror IV

This mirror was exposed during the entire observation time, therefore there are two different measurements of it. The PSF size according to the distance is shown in Figure 5.4, and its pictures are at Appendix A, session A.4.

The Mirror IV focal position is located at 16.75 ± 0.1 m in both measurements, which is inside the expected. Its PSF size in November was $\theta = 0.017 \pm 0.005^\circ$ and in December, $\theta = 0.021 \pm 0.001^\circ$, being within the Consortium requirements but very different. The shape of this mirror changed between the two measurements, not behaving well in the environmental conditions of the site.

5.1.5 Mirror V

As this mirror was broken since its arrival, it was replaced by the Mirror III during November's visit. Therefore, there are no measurements of its focal position.

Figure 5.4 – Data of the PSF size versus the distance measured for the Glass/Aluminium Mirror IV. The smallest PSF point shows its 2f position.

Source: By the author.

5.2 Reflectivity

The environmental conditions, such as wind, rain and dust, are expected to damage the aluminium coating of the mirrors, decreasing its reflectivity. The objective of our observations is to verify this effect.

We have taken reflectivity measurements in two different days, in December/2013 and in June/2014. In the next sections the results for the mirrors I, II, III and IV will be shown.

5.2.1 Mirror I

We took twelve different measurements in the positions showed in Figure 4.13(a). The average of these measurements in both periods can be seen in Figure 5.5.

As we can see, inside the error bars the difference between both measurements was smaller than 3% in parts of the spectrum. However, between 300 and 400 nm, which is the interesting range for the Cherenkov light that reaches the ground, the difference is $\sim 3\%$ in the reflectivity, showing that the coating suffered some damage from the weather.

Figure 5.5 – Comparison between Mirror I reflectivity in December/2013 (blue) and June/2014 (red) with error bars. The interesting range for the Cherenkov light observation is between 300 and 400 nm, where we see a difference of $\sim 4\%$.

Source: By the author.

5.2.2 Mirror II

The measurements were taken in twelve positions, such as showed in Figure 4.13(a). The average of these in both periods are shown in Figure 5.6.

Within the error bars the differences between both measurements are never larger than $\sim 2.5\%$, showing that the Aluminum layer is stable during this period. The largest difference for this mirror is seen between 435 and 470 nm, that are wavelengths larger than the Cherenkov light we are interested in.

5.2.3 Mirror III

Since this mirror is circular, the measurements were taken following the ten points in Figure 4.13(b). The averages in December/2013 and June/2014 are shown in Figure 5.7.

This mirror is the one with the smaller difference between the two measurements in between 300 and 400 nm, with less than 1%. The coating did not suffer any damage from the weather during the observed period.

Figure 5.6 – Comparison between Mirror II reflectivity in December/2013 (blue) and June/2014 (red) with error bars. The interesting range for the Cherenkov light observation is between 300 and 400 nm, where differences are of $\sim 2.5\%$.

Source: By the author.

Figure 5.7 – Comparison between Mirror III reflectivity in December/2013, in blue, and June/2014, in red, both with their error bars. The interesting range for the Cherenkov light observation is between 300 and 390 nm, where there are practically no differences.

Source: By the author.

5.2.4 Mirror IV

This is the measured mirror with the longest exposure time, being in the MTF since May/2013. Twelve measurements were taken according to Figure 4.13(a), and its averages are seen in Figure 5.8.

The difference between the two measurements is the largest of all mirrors, between 3

and 9% in the whole spectrum range analysed. This shows that this aluminum coating suffered a lot of damage of the weather conditions in the site.

Figure 5.8 – Comparison between Mirror IV reflectivity in December/2013, in blue, and June/2014, in red, both with their error bars. The interesting range for the Cherenkov light observation is between 300 and 400 nm, where differences are of more than 8%.

Source: By the author.

5.3 Condensation

In this section we will describe all steps for the condensation time analysis.

5.3.1 Preparing the images

The webcams used in the experiment took colorful pictures of the mirrors. The resolution of the camera was 640x480 pixels. We took an average of the three color channels (red, green and blue) to create grayscale images (Figure 5.9). The Cfitsio (62) library was used to analyse the images. This library generates matrices with the picture pixel intensities in each component.

Figure 5.10 shows a color coded map of the picture in which it is possible to see the mirror and its environment. We cleaned this image by removing the background selecting the mirror as shown by the straight lines. We also removed the central bar support for the following analysis.

Figure 5.9 – Picture from Figure 4.13 transformed into grayscale.

Source: By the author.

Figure 5.10 – Color coded map of a mirror picture and the lines used to remove the background and the central bar of the mirror. The axes x and y are the positions of the pixels in the picture, and the color map is the intensity of each pixel.

Source: By the author.

The water condensed on the mirror surface scatters light making a more bright image in the picture. Figure 5.11 shows two pictures of the same mirror. The left-hand side mirror was condensed and the right-hand side one was not condensed according to visual inspection of the original pictures.

The illumination of the mirror was not uniform as seen in Figure 5.7(a). In order to minimize the effect of the illumination gradient we carefully selected 20 pictures with

Figure 5.11 – Color coded map of (a) a condensed and (b) a not condensed mirror. The axes x and y are the positions of the pixels in the picture, and the color map is the intensity of each pixel.

Source: By the author.

no condensation and used them as a ground level. The average of each pixel in the 20 pictures was used to construct a ground level mirror intensity which was subtracted from all other images to be analysed as shown in the diagram showed in Figure 5.12.

The creation of the histograms is not only useful for the easier observation of condensation, but also for obtaining parameters related to the condensed surface more directly through the application of a code using ROOT (63) environment functions.

5.3.2 Indicative parameters of condensation

We would like to analyse the pictures in a reproducible way by means of a computer routine. We searched the pictures trying to define parameters which could discriminate mirrors with condensation from mirrors without condensation.

With the objective of classifying the mirror pictures in two categories, condensed and not condensed, we searched for parameters related to them. We chose nine relevant parameters, which are described in detail below.

Moments Parameters

We obtained four different parameters directly from the pictures matrices: Average, Standard Deviation, Kurtosis and Skewness.

Figure 5.12 – Steps to make the not condensed mirrors more uniform. We take an average of 20 known not-condensed mirrors and subtract it from all pictures. Here we show an example of this process with a not-condensed mirror, which produces a relative intensity mirror strongly uniform. All graphics have their x and y axes representing the pixels positions and the color map gives the intensity of each pixel.

Source: By the author.

Average

It is the sum of all pixels intensities divided by the total number of pixels in the picture. The average follows the equation

$$\bar{M} = \sum_{i=1}^N \sum_{j=1}^N \frac{P(i,j)}{N} \quad (5.2)$$

where $\mathbf{N}$ is the size of the matrix, $\mathbf{i}$ is the position in the horizontal axis, $\mathbf{j}$ is the position in the vertical axis and $\mathbf{P(i,j)}$ is the intensity of the pixel located in the position $(\mathbf{i},\mathbf{j})$ in the matrix.

With higher intensity the average is larger, which is related with a condensed surface. This can be seen in the histogram in Figure 5.13, where 50 condensed and 50 not-condensed mirror pictures intensity average is plotted. It is clear from this histogram that the average is not enough to separate between the two classifications since both data are overlapped.

Figure 5.13 – Distribution of averages of 50 condensed (black) and not-condensed (red) mirrors. It is clear that this parameter is not enough to separate the mirrors in two different categories.

Source: By the author.

Standard Deviation

The Standard Deviation gives the dispersion of the pixel intensities. It is defined by the equation

$$\bar{\sigma} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N \sum_{j=1}^N (P(i,j) - \bar{M})^2} \quad (5.3)$$

When the dispersion is large there is a big variation of the intensity in the surface, which is related to the beginning of condensation or with rain drops in the mirror surface. We can see the standard deviation distribution in Figure 5.14.

Figure 5.14 – Distribution of standard deviations of 50 condensed (black) and not-condensed (red) mirrors. There are still some values of each kind that superpose, not being enough to classify the mirrors alone.

Source: By the author.

Skewness and Kurtosis

The pixel intensities have a distribution curve for each picture. The Kurtosis parameter is the measure of the peak of this distribution, indicating how high the distribution is around its mean. It is the fourth momentum of the distribution. Its equation is

$$Kurtosis = \frac{\sum_{i=1}^N \frac{(P(i,j) - \bar{M})^4}{N}}{\sigma^4} \quad (5.4)$$

Since not-condensed mirrors are expected to have intensities close to the average, kurtosis is smaller for this kind of mirrors.

Skewness provides a measurements of the asymmetry of the dispersion in relation to its average. It is defined by

$$Skewness = \frac{\sum_{i=1}^N \frac{(P(i,j) - \bar{M})^3}{N}}{\sigma^3} \quad (5.5)$$

Condensed mirrors have intensities ranging from low values, around 20, up to 255, bringing the average between this values. With this large range of values, the skewness value will be larger.

We can see the distributions of this two parameters in Figure 5.15.

Figure 5.15 – Distributions of skewness and kurtosis in 50 condensed (black) and not-condensed (red) mirrors. It is clear that there are a lot of superposed values and that both are not enough alone to classify the mirrors.

Source: By the author.

Haralick's parameters

After obtaining the four parameters directly from the matrices, they were still not enough to separate the mirrors in condensed and not condensed. Therefore more parameters related to condensation were calculated to improve the discrimination of the mirrors. We followed the set of parameters proposed in Haralick et al. article. (64) These parameters are used to discriminate between different patterns in grayscale pictures. Since it can be used to separate pictures of water from earth, we assumed it could separate the mirrors between condensed and not-condensed as well.

In order to obtain the Haralick's parameters it is necessary to create co-occurrence matrices. These matrices depend on the distance and angle between a cell pair of the original picture matrix and have the size of the number of gray levels of the picture (in our case, 256×256). As we wanted the relation between neighbouring pixels, the distance dependency was always one and the angular dependency had four possibilities, 0° , 45° , 90° and 135° , as seen in Figure 5.16. The elements of the co-occurrence matrices, (i', j') , are the sum of the number of all i' followed by j' in the original picture matrix on a given angle.

Figure 5.16 – Angular dependency in a fictitious 3×3 pixels picture.

Source: By the author.

The procedure of creating the co-occurrence matrices can be summarized as follows:

1. Specify which angle will be used (0° , 45° , 90° or 135°);
2. Locate at the original picture all sequences of i' followed by j' in the chosen angle direction, where (i', j') is the component of the co-occurrence matrix);
3. Normalize the obtained matrix according to its angle;

4. Repeat procedure for the other three angles available;
5. Take the average of the four normalized matrices obtained, generating the final co-occurrence matrix needed.

Taking as example the following fictitious picture matrix, based upon the values of Figure 5.16,

$$\begin{pmatrix} 1 & 0 & 1 \\ 0 & 0 & 0 \\ 2 & 2 & 1 \end{pmatrix},$$

the picture has 3 different gray levels: 0, 1 and 2. Therefore, its co-occurrence matrix will have the form of a 3×3 matrix. Choosing the 0° direction, we have to sum how many pairs of each (i', j') position appears horizontally in the picture matrix. The $(0,0)$ pair appears 4 times horizontally, $(0,1)$ 2 times, and so on, obtaining for this angle the following matrix:

$$\begin{pmatrix} (0,0) & (0,1) & (0,2) \\ (1,0) & (1,1) & (1,2) \\ (2,0) & (2,1) & (2,2) \end{pmatrix} = \begin{pmatrix} 4 & 2 & 0 \\ 2 & 0 & 1 \\ 0 & 1 & 2 \end{pmatrix}.$$

In the chosen direction, there are $2 \times (3 - 1)$ pairs on each row, and 3 columns. Therefore, the normalizing factor will be $\frac{1}{3 \times 2 \times (3-1)}$ and the final 0° matrix is

$$M_0 = \begin{pmatrix} \frac{1}{3} & \frac{1}{6} & 0 \\ \frac{1}{6} & 0 & \frac{1}{12} \\ 0 & \frac{1}{12} & \frac{1}{6} \end{pmatrix}.$$

Repeating the procedure for the other three angles, we have

$$\begin{aligned} M_{45} &= \begin{pmatrix} 2 & 1 & 2 \\ 1 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix} \times \frac{1}{2 \times (3-1) \times (3-1)} & M_{90} &= \begin{pmatrix} 2 & 3 & 2 \\ 3 & 0 & 0 \\ 2 & 0 & 0 \end{pmatrix} \times \frac{1}{2 \times 3 \times (3-1)} \\ M_{135} &= \begin{pmatrix} 2 & 2 & 1 \\ 2 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \times \frac{1}{2 \times (3-1) \times (3-1)} \end{aligned}$$

Now that we have the four angular dependant matrices, we calculate their average to finally create the normalized co-occurrence matrix:

$$M = \begin{pmatrix} \frac{1}{4} & \frac{19}{96} & \frac{13}{96} \\ \frac{19}{96} & 0 & \frac{1}{48} \\ \frac{13}{96} & \frac{5}{48} & \frac{1}{24} \end{pmatrix}$$

There were over 6 thousand pictures with 256 gray levels, providing 256 x 256 co-occurrence matrices. These took over 24 hours to be calculated and they had mainly null values, not having enough information to calculate the parameters properly. To optimize the process and increase the population of the matrices, the gray levels were quantified to 32 levels instead of 256, generating 32 x 32 co-occurrence matrices. This decision decrease the processing time by half of the original one, and increase the not null values of the final matrices.

Haralick proposes 14 different parameters to obtain from the co-occurrence matrices, from which we chose five more appropriate to our problem detailed below.

Second Angular Momentum

It measures the homogeneity of the picture. It is calculated through

$$ASM = \sum_{i=1}^{32} \sum_{j=1}^{32} p(i, j)^2 \quad (5.6)$$

where $\mathbf{p(i,j)}$ are the elements of the normalized co-occurrence matrices.

The more homogeneous the picture, the larger is its Second Angular Momentum. Therefore, large Second Angular Momenta are related to not-condensed mirrors, that are made homogeneous through the technique forementioned in this section. Its distribution is shown in Figure 5.17.

Figure 5.17 – Distribution of the second angular momenta of 50 condensed (black) and not-condensed (red) mirrors. Since there are many values superposed, this parameter is not enough to separate the mirrors.

Source: By the author.

Contrast

Measures the local variation of intensities, being larger for not-homogeneous pictures. It is given by

$$C = \sum_{i=0}^{31} n^2 \left(\sum_{i=0}^{32} \sum_{j=0}^{32} p(i, j) \right), |i - j| = n \quad (5.7)$$

Since condensed and wet pictures have strong local variations, large contrasts are connected with these kinds of mirrors. The contrast distribution for condensed and not-condensed mirrors can be seen in Figure 5.18.

Correlation

It gives a measurement of the linear dependency of the gray levels over the image, varying greatly with the angle you choose.

$$Corr = \frac{\sum_{i=0}^{32} \sum_{j=0}^{32} (ij)p(i, j) - \mu_x \mu_y}{\sigma_x \sigma_y} \quad (5.8)$$

where $\mu_x = \sum_{j=1}^{32} \frac{p(i, j)}{32}$, $\mu_y = \sum_{i=1}^{32} \frac{p(i, j)}{32}$ are the means of p_x, p_y and σ_x, σ_y are its standard deviations.

In the case of condensed mirrors the correlation between pixels is larger than in the not-condensed ones, as seen in the distribution of this parameter in Figure 5.19.

Figure 5.18 – Distribution of the contrast of 50 condensed (black) and not-condensed (red) mirrors. This parameter is nearly enough to separate the mirrors, since there are few values that are superposed between the two kinds.

Source: By the author.

Figure 5.19 – Distribution of the correlation of 50 condensed (black) and not-condensed (red) mirrors. There are some values superposed that won't allow the classification of the two mirror types with this parameter alone.

Source: By the author.

Entropy

Measures the randomness of the intensity distribution of the pictures, being smaller for homogeneous ones. It is calculated through

$$S = \sum_{i=0}^{32} \sum_{j=0}^{32} p(i, j) \log(p(i, j)) \quad (5.9)$$

Not-condensed mirrors are more homogeneous than condensed ones. Since entropy gives an homogeneity measurement, its high values can be related to condensed mirrors and its low values to not-condensed ones. This can be seen in the distribution in Figure 5.20.

Figure 5.20 – Distribution of the entropy of 50 condensed (black) and not-condensed (red) mirrors. There are a lot of values superposed, making other parameters necessary for classification.

Source: By the author.

Inverse Different Momentum

It has values higher for images with low contrast, and it's considered the inverse of it.

$$IDM = \sum_{i=0}^{32} \sum_{j=0}^{32} \left(\frac{p(i, j)}{1 + (i - j)^2} \right) \quad (5.10)$$

Large contrasts have strong local variations and are related to condensed mirrors. Since the Inverse Different Momentum (IDM) is the inverse of the contrast, small IDM values are related to condensed mirrors, and large values to not-condensed one. This is shown in the distribution in Figure 5.21.

With these nine parameters, it is now possible to use classification techniques to separate our mirrors into condensed and not condensed.

Figure 5.21 – Distribution of the inverse different momentum of 50 condensed (black) and not-condensed (red) mirrors. Since most values are superposed, it can not be used alone to classify the mirrors.

Source: By the author.

5.3.3 Classification Techniques

Classifiers are mechanisms used to discriminate data in different categories through given parameters. There are two kinds of classifiers, supervised and not supervised. The supervised ones receive data with instances previously classified to train themselves before attempting to separate the instances, while the not supervised ones rely only in patterns made by the provided parameters. In our analysis we chose to work with supervised classifiers.

There are several algorithms of supervised classifiers, and since we did not know which one would work for us, we used a java interfaced program called Weka. (65) This software has several classification techniques implemented and it has a very easy mechanism to compare all of them. We tested three different techniques:

- **Naive Bayes:** This is the most simple classification algorithm used currently, and it is commonly used in the first attempt of classification because of its simplicity and fast computational time. It considers all parameters equally important and conditionally independent. It uses the Bayes Theorem (66), i.e., the probability that one event occurs in consequence of another, to classify instances.

These algorithms bring good results even when the probability estimative is not very accurate, being only necessary that the maximum probability is given to the correct parameter only. It can be improved by removing redundant parameters discovered

through continuous testing of the method accuracy.

- **Representative Tree: (67)** This model is based on Tree classification. It initially places all parameters in the *root* of the tree, partitioning them afterwards based on selected attributes to divide them into different classes, creating *branches* and *leaves*. This process only stops once all examples given for a branch belong to the same class or when there are no more attributes to partition. This is a simple technique and it allows the reduction of errors by choosing better parameters and to cut *leaves* that are leading to errors.

The Representative Tree algorithm in particular is a Tree classifier that uses the smallest gain/variance ratio to stop the branching process. It only sorts values for numerical attributes once in order to decrease the computational time and errors caused by repeated branching of the same parameter.

- **Random Forest: (68)** It combines several trees from several samples chosen by the classifier as a training set. It then selects a random subset of feature to classify the parameters, repeating this process until arriving at the best accuracy it can provide.

The forests errors are directly related to each individual tree used to build it and to the correlation between the parameters provided. If the individual trees are strongly accurate, the random forest generated by it will have small errors. If the parameters are strongly correlated, the forest error will be large. Therefore, it is necessary to balance between the accuracy of the individual trees and small correlation between the parameters in order to obtain the smallest error for the forest classifier.

As these are supervised classifiers, they require a training procedure previous to the classification itself to optimize the results. For the training we used a total of 100 pictures, 50 classified as condensed and 50 as not condensed. We have selected the training set by eye inspection. We then tested which parameters increased the classifier accuracy before finally supplying all the instances we wanted to classify.

5.3.4 Select Condensed Mirrors

In order to select which mirrors are condensed from all the pictures taken, we applied the classification techniques mentioned in Section 5.3.3 in Weka. Not all parameters

explained were used at the same time, as shown in Table 5.1. Different combinations of the parameters were tested repeatedly until the highest accuracy was reached.

Table 5.1 – Parameters used in the classification for each technique.

Mirror	Naive Bayes	Random Forest	REP Tree
II	A. Mom, Contrast,	Average, RMS,	
	Correlation,	Contrast, Correlation,	Contrast.
III	Entropy.	I.D.M.	
	RMS,	RMS, Kurtosis,	RMS,
IV	Skewness,	A. Mom., Contrast,	Skewness,
	Kurtosis,	Correlation, Entropy,	Kurtosis.
	Correlation.	I.D.M.	
	Contrast,	Average, RMS,	Skewness,
	Correlation,	A. Mom., Contrast,	A. Mom.,
	Entropy.	Correlation, Entropy,	Contrast,
		I.D.M.	Correlation.

Source: By the author

At first we applied the three mentioned techniques with several combinations of the given parameters in the 100 mirrors previously classified set. Once we obtained the best accuracy as possible, we applied the same technique with the chosen parameters in the full data file not yet classified. The program generates a text file with each mirror classification. After verifying each picture in order to qualify the technique accuracy, we created another data set with all mirrors correctly classified. With this data set, Weka can compare its own classification with the real data and provide a confusion matrix. This matrix shows how many mirrors were correctly classified when the column and line names are the same and the wrongly classified ones when the column and line names are different. We can see in Table 5.2 the confusion matrices for Mirrors II, III and IV.

The classification errors, i.e., the mirrors classified into the wrong categories, of the three mirrors are below 9%. However, while checking this results, we discovered that most of misclassified condensed mirrors had a dirty surface that confused the classifier because of its similarities with the condensed surfaces (Figure 5.22). In order to separate the dirty mirrors from the condensed one, we did a refinement of our classification. This was done through the addition of 50 pictures of dirty mirrors in our training set. The obtained Confusion Matrices are shown in Table 5.3.

The number of dirty mirrors that still confused with condensed one is now sufficiently small to proceed with the analysis. The summary of the accuracy of each classification technique for both types of mirrors is shown in Table 5.4. The following step is to select which pixels are condensed in the mirrors.

Table 5.2 – Confusion Matrix of (a) Mirror II, (b) Mirror III and (c) Mirror IV.

(a)		
Condensed	Not-Condensed	
1016	85	Condensed
331	4684	Not-Condensed

(b)		
Condensed	Not-Condensed	
1197	132	Condensed
142	4721	Not-Condensed

(c)		
Condensed	Not-Condensed	
889	165	Condensed
334	4614	Not-Condensed

Source: By the author.

Table 5.3 – Confusion Matrix of the refinement classification for Mirrors (a) II, (b) III and (c) IV.

(a)		
Dirty	Condensed	
314	17	Dirty

(b)		
Dirty	Condensed	
137	5	Dirty

(c)		
Dirty	Condensed	
329	5	Dirty

Source: By the author.

Figure 5.22 – Example of (a) a dirty mirror confused with a (b) condensed one.

Source: By the author.

Table 5.4 – Tables showing the precision of classification for each technique for (a) condensed and (b) not condensed mirrors.

(a)			
Condensed mirrors			
Mirror	Naive Bayes	Random Forest	REPTree
II	85.7%	93.4%	92.3%
III	72.4%	88.1%	90.1%
IV	47.4%	44.8%	62.9%

(b)			
Not condensed mirrors			
Mirror	Naive Bayes	Random Forest	REPTree
II	95,3%	93.4%	93.4%
III	96.8%	98.7%	97.1%
IV	94.7%	98.2%	62.9%

Source:By the author

5.3.5 Select Condensed Pixels

In order to discover which area of the mirror is condensed and for how long, it is necessary to know which pixels from the pictures are or are not condensed. This is different from what was done in the previous section. The analysis developed in the previous section had the intention to select mirrors with some condensation in it. In this section, we are going to analyse the mirrors classified as condensed and measure the area of this mirror which were condensed.

In this section we don't use the average mirror shown in Section 5.3.1. Since there is a large difference in the illumination in the superior and the bottom part of the mirrors, we decided to discover a function that related the pixel height with its intensity for each classified mirror. In order to do that, we chose ten different pictures in which there is a fully condensed or not condensed slice in the full length of its surface (Figure 5.23), with 3-5 pixels width. By taking the average of every line at every 5 pixels in height, we obtained the graphic shown in Figure 5.24.

Figure 5.23 – Slices taken from a condensed and not condensed mirror, respectively.

Source: By the author.

The intensity of the pixels is higher near the top of the mirror, where the lighting is stronger, and the condensed points are more intense than the not condensed ones, following a linear function while the not condensed points follow a polynomial one. In order to verify if these two functions were sufficient to classify all pixels from the condensed mirror pictures, we plotted the pixel intensities versus height for all the condensed pictures, obtaining the graphic shown in Figure 5.25.

Figure 5.24 – Intensity as a function of height for Mirror II. The red points represent the condensed mirrors, and the blue the not condensed ones.

Source: By the author.

Figure 5.25 – All pictures pixels intensities as a function of height for Mirror II, with the red line being the condensed function and the black the not condensed one.

Source: By the author.

There were a lot of pixels far from both of the functions. Since there were wet mirrors among the condensed ones, we separated ten wet pictures (Figure 5.26) and followed the same procedure done with the condensed and not condensed ones, obtaining the graphic shown in Figure 5.27.

Figure 5.26 – Slice taken from a wet mirror.

Source: By the author.

Figure 5.27 – Intensity as a function of height for condensed (red), not-condensed (blue) and wet (pink) pixels of the Mirror II condensed mirrors.

Source: By the author.

Considering the error bars of the pink points, a lot more pixels between the condensed and not-condensed curve are covered, allowing a more precise classification. Therefore, we adjusted a curve in the *RMS–Average* pink points, and used it as a "blind pixel" classifier, while the blue one was the "observable pixel" one (Figure 5.28).

The classification is done following three steps. First, locate the pixel height and intensity. Then, calculate the distance from this point to both blind and observable curves

Figure 5.28 – Final curves used for pixel classification in the Mirror II. The purple line represents the "blind" pixels and the blue the "observable" ones.

Source: By the author.

in the same height. Finally, the smallest distance measured indicates the classification of the pixel.

This technique was repeated for the Mirror III. However, since its fabrication is different from the Mirror II, some issues happened in the classification process. The mirror is dielectric, reflecting light only in a particular wavelength range and being transparent to the rest of the visible spectrum. Therefore, it is not possible to differentiate between not condensed pixels and completely wet ones, as we can see in the functions plotted in Figure 5.29, increasing the error in the calculation of the condensed time shown in Section 5.3.6.

Figure 5.29 – Intensity as a function of height for Mirror III. The red line represents condensed pixels, the pink partially wet ones, the blue not condensed pixels and the purple completely wet ones.

Source: By the author.

The pixel classification of Mirror III was made using the pink and the blue functions from Figure 5.29.

This analysis could not be done for the Mirror IV because of its illumination and condensation conditions. As shown in Figure 5.30, this mirror condensed mostly in the superior part, and it was not possible to obtain a full length slice from its pictures. Also, the intensity of the pixels condensed and the not condensed ones were very similar, what made the differentiation not possible with this technique.

Figure 5.30 – Condensed and not condensed pictures examples for Mirror IV. It is not possible to obtain a slice of the full height of condensed mirrors in this case.

Source: By the author.

5.3.6 Calculate condensed time

With the pixels classified as condensed, now it is possible to calculate for how long they remained that way. Each picture represents ten minutes of observation time, and for Mirror II and III the total number of pictures taken is of the order of 6000, providing us with 60000 minutes of observation or 1000 hours. The percentage of time each pixel was condensed for both mirrors is shown in Figure 5.31. The superior part of the mirror was cut because the intensity of the pixels in that region was saturated and could not be classified.

For Mirror II the condensed time is, at maximum, $18 \pm 2\%$ or 184 ± 20 hours, with an average time of condensation of 5.32 hours at once. For Mirror III the condensed time is $19 \pm 2\%$ or 196 ± 21 hours, with an average of 3.17 hours at once. These errors take in account misclassified condensed mirrors found by visual inspection. Both time periods are similar, however the percentage of Mirror III is underrated because the differences between

a not-condensed and fully wet mirrors are too small, leading to the misclassification of some mirrors and pixels.

Figure 5.31 – Percentage of condensed time for (a) Mirror II and (b) Mirror III. The x and y axis represent the pixels position. The color map is the percentage of condensed time from 0 to 18 or 19%.

(a)

(b)

Source: By the author.

In Figure 5.32, we can see the time related to the area condensed for both mirrors. The graphic (a) shows that the Mirror II spends nearly 75% of its condensed time (~ 138 hours) with more than 10% of its surface condensed, and $\sim 35\%$ (64.4 hours) with more than 80% of its surface condensed. The graphic (b) shows that the Mirror III spends all its condensed time with its surface between 18 and 26% condensed. However, this information is not fully reliable because completely wet mirrors, which would give more than 60% of its area as condensed, are considered not-condensed in the previous classifications.

Figure 5.32 – Time versus percentage of condensed area versus integral of time for (a) Mirror II and (b) Mirror III.

(a)

(b)

Source: By the author.

CHAPTER 6

Conclusions

In this work three different tests made in San Antonio de los Cobres were described in Chapter 4, with their results shown in Chapter 5. The first test was the 2f position and Point Spread Function measurements, which showed that the mechanical characteristics of the four analysed mirrors were constant, while their coating suffered some variations with the weather. The reflectivity analysis showed variations in the observed spectrum for all aluminium mirrors, showing that the coating is not sufficiently resistant for the SAC site. The last test made was the condensation time. Through the analysis of over 6000 pictures we discovered that the mirrors remained condensed for nearly 20% of the observed time period, with results similar for the dielectric and aluminium mirrors analysed.

The conclusions for the 2f position and Point Spread Function measurements are made in Section 6.1, for the reflectivity analysis in Section 6.2 and for the condensation time in Section 6.3. To close this work, we will present its final conclusions in Section 6.4.

6.1 Variation of focal position

The location of the focal position and the Point Spread Function (PSF) value were obtained through a 2f system (Figure 4.6), developed at Instituto de Física de São Carlos. Using a laser distance measurer we could locate the focal position once the image formed by the blue LED was the smallest, and we considered the size of this image as the PSF of the telescope. The Cherenkov Telescope Array requires that the PSF is $< 0.18^\circ$ around its center.

Two measurements were made in November/2013 and December/2013 through pictures taken every 0.5 m from 30 until 34 meters of the mirror. Mirror I had only one measurement because it was not exposed in November yet, and has a focal position around 16.25 ± 0.01 meters and a PSF of 0.035° . Mirror II remained with its focal position around 16.50 ± 0.01 meters during both periods, and varied 0.009° in its PSF, suffering a very small variation in the mirror smoothness. Mirror III had a stable focal position around

15.4 ± 0.2 meters and its PSF size of 0.046° remained the same. Mirror IV, which had the longest exposure time, kept its focal distance at 16.75 ± 0.01 meters and its PSF varied 0.008° , showing a small variation in the surface. All mirrors kept their focal position constant, and Mirrors II and IV varied their PSF in 23% and 17%, showing a change in the smoothness of its external coating.

6.2 Variation of reflectivity

These measurements were taken with the spectrometer Jaz[®] of Ocean Optics[®] such as seen in Section 4.3 during two trips to San Antonio de los Cobres, in December/2013 and June/2014. By using a reference spectrum (Figure 4.11), it was possible to obtain the real reflectivity values in the spectrum range of 300 to 500 nm measured locally in each mirror. In order to obtain the full mirror reflectivity an average of different positions was calculated, with twelve points taken for the hexagonal mirrors (Figure 4.13(a)) and ten for the circular ones (Figure 4.13(b)). The objective of these measurements was to test the quality of the aluminum and dielectric coating of each mirror through the difference in the reflectivity percentual in the Cherenkov light emitting range.

The results for each mirror were showed in Figures 5.5, 5.6, 5.7 and 5.8 in Section 5.2.2. In Mirror I, the reflectivity above 350 nm did not vary, while below it the difference was 3-6% during the seven months of exposure, which gives less than 1% of change per month. In Mirror II, the differences are always smaller than 3%, which shows a more resistant coating. Mirror III, the glass/dielectric one, had no change in its reflectivity between 300 and 380 nm, which was expected since it is used in the H.E.S.S. experiment, which had no reports on changing its mirror facets since 2004. Mirror IV had the largest changes in reflectivity, from 3-12%, showing the weaker coating of the exposed prototypes. Therefore, we concluded that the dielectric coating endures the weather conditions more strongly than the aluminium one. We also concluded that the present technique of coating with aluminium needs to be improved. The deterioration of mirrors coated with aluminium (minimum 1% per month) is not acceptable for an experiment supposed to run for at least 20 years.

6.3 Condensation measurements

Through the pictures taken automatically in the site during the night (Figure 4.13) we calculated the condensed time of two mirrors, Mirror II and III, during the period of December/2013 until April/2014. We obtained nine different parameters from the pictures, four directly from its matrices and five from its co-occurrence matrices (Section 5.3.2) in order to classify them in two categories, condensed and not condensed.

Once the parameters were obtained, we used the Random Forest technique to do the classification (Section 5.3.3). Both mirrors were classified with less than 9% error, but we discovered that some dirty mirrors were mistakenly selected as condensed. After a refinement of the classification we obtained less than 5% error in the final classification.

With the pictures in two categories, it was necessary to develop a technique to decide which pixels were condensed in them (Section 5.3.5). Since the difference of lighting from the upper part to the bottom was clear, we decided to create curves of pixel intensity versus height for the three kinds of pixels we had, not-condensed, condensed and wet, obtaining the graphics showed in Figure 5.28 for Mirror II and in Figure 5.29 for Mirror III. However, since the not-condensed and completely wet surfaces of Mirror III was very similar in intensity, we probably had a smaller number of condensed pixels than there actually was. This was also the same problem that did not allow the application of this technique in Mirror IV.

Each picture represents 10 minutes of observation time and we have over 6000 pictures, what means there are ~ 1000 hours of observation. Figure 5.32 showed the percentage of condensed time each pixel remained during the four month period of exposition. For Mirror II, the pixel that remained condensed during the longest time during $\sim 18\%$ or ~ 184 hours, while Mirror III had $\sim 19\%$ or ~ 196 hours. Therefore, the site of San Antonio de los Cobres loses 20% of observational time only because of condensation. However, since the percentage for Mirror III is probably underrated because of the confusion between not-condensed and completely wet pixels, dielectric mirrors would not be a good choice for this site.

6.4 General conclusions

The tests made in San Antonio de los Cobres showed that the site has a high condensation time. This brings the observational time close to the lower limit aimed by the CTA collaboration.

The condensation analysis could have provided better and more precise results if the exposition time could have been longer, around one year, and if there was a light calibration system. Also, a model could be developed to predict the condensation of the mirror surfaces with weather conditions in the site and over the surfaces were obtained in a high number of days when the mirror was condensed. The correlation with the weather was planned as part of this work, however the weather station did not work in SAC and we could not analyse its data. This study could only be done through data with local information since the temperature, pressure and humidity near the mirror is necessary.

All prototype mirrors sent resisted well to the environmental conditions they were exposed to mechanically, and Mirrors I and IV had some degradation in their optical properties that can be fixed by applying a better coating on the surfaces.

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APPENDIX A

*2f system pictures***A.1 Mirror I**

The pictures for Mirror I were taken on December/2013, and they are shown at Figure A.1.

A.2 Mirror II

There are two groups of pictures of the Mirror II, taken in November/2013, seen at Figure A.2 and December/2013, seen at Figure A.3.

A.3 Mirror III

Pictures taken on November/2013 are shown in Figure A.4 and the ones taken on December/2013 in Figure A.5.

A.4 Mirror IV

Pictures taken on November/2013 are shown in Figure A.6 and the ones taken on December/2013 in Figure A.7.

Figure A.1 – Images of Mirror I between 30 and 34 meters distance from the mirror.

(a) Image at 30 meters from the mirror.

(b) Image at 30,5 meters.

(c) Image at 31 meters.

(d) Image at 31,5 meters.

(e) Image at 32 meters.

(f) Image at 32,5 meters.

(g) Image at 33 meters.

(h) Image at 33,5 meters.

(i) Image at 34 meters.

Source: By the author.

Figure A.2 – Images of the Mirror II between 30 and 33.5 meters distance from the mirror in November/2013

Figure A.3 – Images of the Mirror II between 30 and 34 meters distance from the mirror in December /2013

(a) Image at 30 meters from the mirror.

(b) Image at 30,5 meters.

(c) Image at 31 meters.

(d) Image at 31,5 meters.

(e) Image at 32 meters.

(f) Image at 32,5 meters.

(g) Image at 33 meters.

(h) Image at 33,5 meters.

(i) Image at 34 meters.

Source: By the author.

Figure A.4 – PSF of the Glass/Dielectric Mirror III between 30 and 33.5 meters distance from the mirror.

Source: Courtesy of Clementina Medina

Figure A.5 – PSF of the Glass/Dielectric Mirror III between 30 and 34 meters distance from the mirror.

(a) Image at 30 meters from the mirror.

(b) Image at 30,5 meters.

(c) Image at 31 meters.

(d) Image at 31,5 meters.

(e) Image at 32 meters.

(f) Image at 32,5 meters.

(g) Image at 33 meters.

(h) Image at 33,5 meters.

(i) Image at 34 meters.

Source: By the author.

Figure A.6 – PSF of the Glass/Aluminum Mirror IV between 30 and 33.5 meters distance from the mirror.

Figure A.7 – PSF of the Glass/Aluminum Mirror IV between 30 and 34 meters distance from the mirror.

(a) Image at 30 meters from the mirror.

(d) Image at 31,5 meters.

(g) Image at 33 meters.

(b) Image at 30,5 meters.

(e) Image at 32 meters.

(h) Image at 33,5 meters.

Source: By the author.

(c) Image at 31 meters.

(f) Image at 32,5 meters.

(i) Image at 34 meters.